Spatial Analysis of Communal Grazing Resources and their Utilisation by Sheep in the Highlands of Mexico

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"Si sobre dos cabezas cae la nieve es dulce el corazón caliente de la casa..."

- Pablo Neruda -

To Deborah...

...because with the conclusion of this thesis we are setting off to new horizons;

because I came to this country in the pursuit of an academic venture, and now that it is time to leave, I am doing so with a companion for life and a joyful heart.

Declaration

I hereby declare that this thesis has been composed by me and that all work presented in this thesis is my own unless specifically otherwise stated.

August 19, 2002

Abstract

This thesis is concerned with analysing the interactions between smallholder sheep farming systems and the sustained maintenance of communal grazing resources in the temperate region of Mexico. The study was carried out in the parish of Coajomulco, which is located in the mountainous region south of Mexico City. Sheep production is a traditional agricultural activity in the region and extensive grazing is practised in the parish's communal forest. In 1988 the area was decreed as protected by the Ministry of Environment, and agricultural practices were highly regulated. Although sheep flocks could still have access to the forest, the establishment of an exclusion zone resulted in the inability of sheep farmers to make use of 48 % of the communal grazing area. Thus, the objectives of this thesis were concerned with finding a way of enhancing the development of the local smallholder sheep farming whilst concomitantly protecting the forest ecology.

The ultimate objective of this thesis was to develop a spatial optimisation model for the grazing management of the communal land. This model produced the optimal distribution of flocks in time and space according to the characteristics of both the grazing resources and the sheep population. Prior to the development of the optimisation model, it was necessary to characterise the basic elements that affected the supply and demand of forage. Thus, under a farming systems research framework, the plant and animal elements of the farming system were characterised. The managerial and biological influences that defined the sheep grazing patterns were investigated and their resulting effects discussed. Participatory techniques were included as the core of the characterisation methodology. Findings derived from the characterisation were utilised to assist in the development of a geographical information system (GIS) and the application of biological simulation models. Two models, one that simulated flock dynamics and another that simulated sheep performance, were used. Subsequently, a two-way link was established between the simulation models, the GIS and the optimisation model.

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Chapter 1

General Introduction

The major challenge for Mexican agriculture is both to provide food for a population of around 100 million and to do so under complex conditions of deregulated international trading, abolition of subsidies and the creation of regulations related to environmental protection. The agricultural sector in Mexico has developed in two different ways to produce a highly developed and intensive market-orientated agriculture, alongside a smallholder "campesino" agriculture, which is mainly subsistence-orientated. Economic and political changes in the agricultural sector in Mexico affect this broad range of farmers in different ways. Thus, at various levels within agricultural systems, there is the necessity to produce alternative strategies and to facilitate better use of the resources to adjust to new scenarios and conditions. To achieve these developments, the scientific and technical communities need to be involved in the design of analysis tools capable of assisting farmers with feasible solutions.

This thesis is concerned with the sheep industry of Mexico, and in particular with the smallholder farming systems. As the driving objective, the work presented here aims to contribute to the enhancement of the livelihoods of those traditional smallholding farmers that have found in sheep a suitable way of living.

The project of this thesis was based at the *Centro de Enseñanza, Investigación y Extensión en Producción Ovina* (Centre for Teaching, Research and Extension in Sheep Production) or CEIEPO. This centre belongs to the Faculty of Veterinary Medicine and Animal Husbandry of the National University Autonomous of Mexico (UNAM). CEIEPO is located in the municipality of Huitzilac, in the highlands of central Mexico. In addition to research and teaching activities on sheep production systems, the centre provides technical assistance and technology transfer to the nearby farming communities through its extension services division (ESD). CEIEPO's extension services team has developed an especially solid communication link with the parishes that integrate the municipality of Huitzilac: Tres Marias, Huitzilac, Fierro del Toro and Coajomulco.

The overall purpose of the study described in this thesis is to contribute to the efforts of the ESD in search of sheep farming strategies that are economically, socially and ecologically sustainable for the farming communities of the municipality of Huitzilac. This thesis intends to produce a optimisation model that responds to the ESD's needs to breach the logistical gap between individual-farm assistance and the local, regional and national constraints that smallholder sheep farming systems confront in Mexico.

The objective of this thesis was to build a linear-programming model for the spatial optimisation of the grazing distribution patterns of the communal land in the study area. The optimisation model was linked to a geographical information system and included the characterisation of the animal and plant elements of the grazing system. The optimisation model produced the optimal distribution of flocks in time and space according to the characteristics of both the grazing resources and the sheep population. Participatory techniques and simulation modelling were used throughout the development of this thesis. All this methodologies were dynamically linked for the exchange of information under a farming systems approach.

The parish of Coajomulco was chosen as the study area for this research due to the higher relative abundance of sheep farmers, and an existing conflict of interests between conservation issues and grazing practices. During the last six years, CEIEPO has produced significant information regarding Coajomulco's smallholder sheep farming systems. Although this information was invaluable for the preparation of this project, the information presented here was collected, updated and processed exclusively for this thesis. Other sources of information related to Coajomulco are properly cited or acknowledged.

This study is focused on the use of Coajomulco's grazing resources, and its development lies on the grass roots of any grazing system: matching the supply of edible material to the demands of the animal element of the system. This principle of the theory of grazing systems of Voisin (1949) is complemented with grazing ecology principles extensively described in Gordon and Illius (1993), Illius and Hodgson (1996) and Hodgson and Da Silva (2000). Thus, the study of Coajomulco's grazing system is presented organised in three sections: i) the animal element of the system, ii) the plant element of the system, and iii) the plant-animal interactions.

1.1 Thesis outline

Chapter 2 provides a review of the smallholder sheep farming systems in Mexico. It sets the scene for understanding the constraints that have hindered the development of sheep production in Mexico. The importance of the role of sheep within a smallholder agricultural system is highlighted and a review of their potential for development is given. Finally, Chapter 2 puts forward the role of the scientific community and policy makers in the enhancement of smallholder sheep farming systems in Mexico.

In Chapter 3, a description of Coajomulco's sheep farming system is given. The current scenario of conflict of interests between environmental conservation policies and sheep farming is presented. This chapter also presents the description of the animal element of the system through the characterisation of the local farming system.

The description of the plant element of the system comprises chapters 4 and 5. The former contains information that can be described as relating to the variability of the forage resources in a spatial context, since it deals with the botanical composition of the plant communities and their spatial arrangement. Chapter 5 focuses on the characteristics that are inherent in the morpho-physiological properties of the plant, e.g. productivity and nutritional composition.

In Chapter 6 attention is turned towards the plant-animal interactions. First, the theoretical background is considered for the development of the analysis. Subsequently, the chapter is divided in two main sections; the first one looks at the abiotic factors of the plant-animal interactions, whilst the second is concerned with the biotic factors. The former are addressed through geographical information systems (GIS) techniques whilst the latter are addressed through the application of simulation and theoretical models.

Chapter 7 is concerned with the development of a spatial optimisation model that brings together the analysis presented from chapters 4 to 7. This model is developed to identify the best use of the grazing resources so that sheep grazing does not compromise the ecological balance of the system.

The conclusions of this work are presented in Chapter 8. This chapter also looks at the areas of future research that would facilitate further understanding and improvement of the issues exposed in this thesis.

1.2 Final remarks

Although the study concentrates on the use and production of forage resources, it is developed under a conceptual framework that has taken into consideration the following points:

(i) Whether sheep farming in Coajomulco represents an option for the sustainable use of the local forest resources.

(ii) Whether sheep farming under the current or an improved management regime can positively affect the living standards of Coajomulco's smallholders. If so, whether sheep farming could indirectly decrease illegal forest exploitation by means of providing an alternative attractive economic activity.

(iii) Whether the methodologies and analysis presented in this thesis can provide local extension services (i.e. CEIEPO's) with a decision-support system to assist them in their study of Coajomulco's smallholder sheep farming systems.

(iv) Whether such decision-support system can deliver, on one hand, practical and feasible recommendations to Coajomulco's sheep smallholders and, on the other hand, guidelines for local and regional policy makers.

(v) Whether such a decision-support system can contribute to the design of an integral plan for the ecological conservation of Coajomulco's landscape.

Chapter 2

Sheep Production Systems in Mexico and the Characteristics of Smallholding Farms

2.1 General overview of sheep production in Mexico

The evolution of sheep production systems in Mexico has been shaped by a variety of social, economic and ecological factors. The sheep production systems that are currently found across the country are the result of the dynamic development of Mexican agriculture. Since the Spaniards introduced the first sheep flocks, the production systems were defined by the wide range of climates across the country and the resulting availability and seasonality of grazing resources. Nowadays, issues such as land tenure, market access, and the free trading of international agricultural commodities, are influencing the dynamics of these sheep production systems.

Some of the contents of this chapter have been included in:

González-Estrada E., Fawcett R.H. and Herrero M. (2002): Smallholder sheep farming systems in Mexico and their potential to enhance sustainable rural development. *Outlook on Agriculture* (Submitted paper, August 2002).

Sheep production systems are distributed across all of Mexico. The sheep population is estimated to be around 6 million (SAGARPA, 2002). According to Sánchez del Real and Martínez (1998), 49% of the total sheep population is located in the centre of the country, 26% in the north, and 25% in the tropical region. The predominant genotype is the Criollo sheep, which emerged as the result of crossbreeding between imported pure breeds (Rambouillet, Suffolk, Hampshire, Dorset) and the original Spanish flock introduced after the conquest (Merino, Latxa, Churra). Hair sheep, mainly Pelibuey and Barbados Blackbelly introduced from the Caribbean islands, make up 23% of the Mexican sheep population (Medrano, 2000). This variety of sheep is particularly found in the arid, semi-arid and tropical regions of the country.

Sheep farming systems in Mexico can be grouped into intensive or extensive systems according to the scale of resource utilisation. The degree of intensification is determined by factors such as availability of grazing resources in space (grazing area) and time (seasonality), price of purchased inputs, and labour cost. In an intensive system the amount of financial and labour inputs is high. Sheep can either be stall-fed and be given a diet with a high content of grain and other agricultural by-products, or have access to improved grasslands with intensive grazing management. Intensive systems may also make use of improved breeds by the inclusion of selected animals or imported livestock. Thus, these systems demand considerable management expertise from the farmer. As a result, in these systems the financial turnover is usually high as a consequence of shorter productive cycles and better productive parameters. On the other hand, if the level of resource utilisation is minimal, the production system can be identified as extensive, or as a low-input system. In these systems, the financial investment to improve the quality of either the livestock or the supplied feed is very small or null. Sheep can be found grazing on communal land, in arable areas after harvesting, or fed with the household surpluses and agricultural by-products.

Mexican sheep farming systems can also be classified according to the agricultural activity that predominates within the system as proposed by Winrock International (1983). Following this classification, systems can be regarded as i) animal-based, ii) crop-based or iii) mixed systems. In the animal-based system, sheep are the major or only component of the system, whether they are raised under an extensive grazing or intensive stall-feeding system. In the crop-based system, sheep play a minor role relative to the cropping activity, whether they are in specialised cash-crop commercial farms, or in smallholder farms. Finally, in a mixed system the importance of the sheep relative to the crop element is indistinguishable. Although there is not precise information about the percentage of sheep farms that can be classified with this system, Medrano (2000) suggests that 34% of Mexican sheep farmers undertake sheep production as the only economic activity.

2.2 Some data about the sheep industry in Mexico

The final output of Mexican sheep farming systems is very specific: meat. Dairy sheep flocks are practically non-existent and the wool industry that put Mexico as the second largest world wool exporter during the latter part of the 18th century has almost vanished. Since the collapse of international wool prices in 1989 and 1990, wool has become a by-product that, despite maintaining an important niche in the artisanal handcraft industry of some regions, has lost its commercial value as a main production objective. Thus in general terms, all the sheep farming in Mexico is meat-production orientated.

Sheep meat has a high domestic demand as a result of its inclusion in Mexican cuisine in the form of a very popular dish known as "barbacoa". The meat quality required for this dish has driven sheep farming systems towards mutton rather than lamb production. The consumption of sheep meat in form of "barbacoa" is particularly high in the central region of the country and the domestic production has not been able to satisfy this demand (Ramírez and Cuéllar, 1995; Losada *et al.*, 1996).

The inability of the domestic sheep sector to supply the high demand of sheep meat has provoked the need to import large amounts of meat. Figure 2-1 shows the national consumption of sheep meat from 1976 to 2000 with data from FAO (2002). The consumption from domestic production and imports is differentiated. It can be noticed that particularly during the 1990's, consumption relied on imports. In 1985 the deregulation of international trading in agricultural commodities provoked large imports of sheep livestock and frozen meat from, in particular, the USA, Australia and New Zealand (Torres, 1998). The Agriculture Ministry reported that the imported sheep products in 1999 accounted for more than 60% of the total sheep meat consumed in Mexico (SAGARPA, 2002) (Figure 2-1). In 1998, the price of mutton imported from USA was 20 to 30% less than local lamb (Sánchez del Real and Martínez, 1998). The cheaper market value of these imports put commercial farms in a disadvantageous position, forcing them to seek strategies to improve the productivity and profitability of their systems, and to adapt to the shifting market structure.

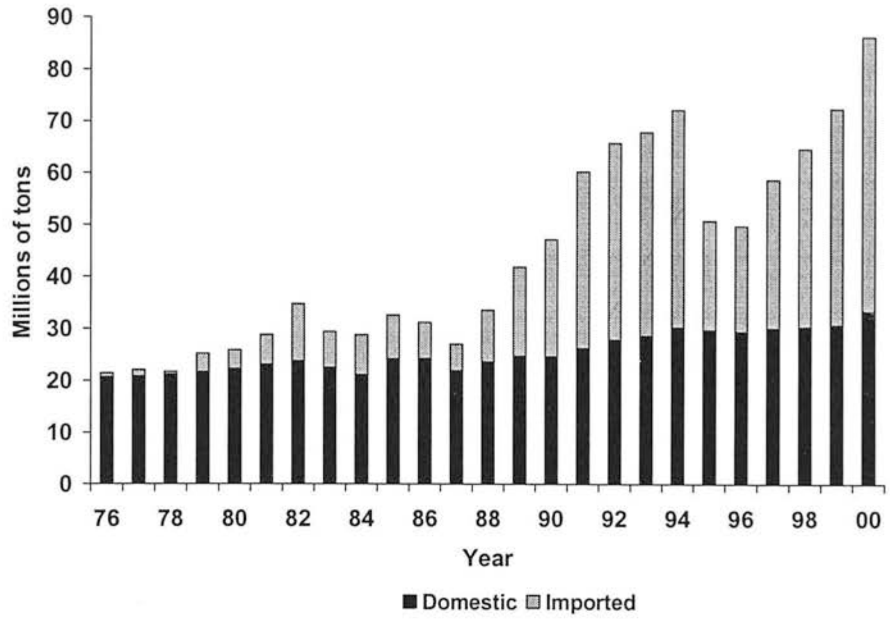

Figure 2-1 Contribution of domestic production and imports to the national consumption of sheep meat

Despite the high demand for sheep meat, the sheep industry in Mexico occupies the last place in the contribution to the gross domestic product (GDP) in the agricultural sector. Cheaper imports are not the only cause of the low contribution of the sheep sector in Mexican agriculture. In parallel with commercial sheep farms, sheep production has found a niche in smallholder production systems which, in relative terms, contributes little to the GDP, but contributes substantially to the livelihoods of poorer households. Around 80% of the sheep stock is held within "campesino" (peasant) smallholdings with low technological and financial inputs (Alvarez, 1995; Sánchez del Real and Martínez, 1998).

2.3 Smallholder sheep farming systems in Mexico

Smallholder systems in Mexico have developed under a wide combination of ecological, social and economic conditions. The complexity of a smallholder sheep farming system makes the use of a single classification criterion unsatisfactory to describe the functioning of such a system. Neither regarding it as intensive or extensive, nor applying Winrock International's (1983) criterion would be sufficient to classify it. This is mainly due to the fact that although predominantly subsistence-orientated, these systems also undertake commercial activities and set market-orientated objectives. Thus, for the purpose of this work, the conceptualisation of "smallholding" focuses on the household as the generator and beneficiary of the system's inputs and outputs. In this context, smallholder sheep farming systems can be considered as such, regardless of the ecological and socio-economic conditions that define flock size and/or feeding resources. Therefore, in smallholder systems the family household is the social unit for mobilising agricultural labour, managing productive resources, and organising consumption (Netting, 1993; McDermott *et al.*, 1999).

2.3.1 Constraints on the development of smallholder sheep farming systems in Mexico

There are several factors that have hindered the development of sheep smallholder systems in Mexico. Some of these factors are not exclusive to the sheep sector of Mexican agriculture but also pertain to many agricultural smallholder systems. Some authors have listed various constraints that affect sheep farmers in Mexico, and particularly smallholders (Arteaga, 2000; Sagarnaga *et* al., 2000; Suárez and Sagarnaga; 2000). In this work, these constraints are summarised as three factors: poor flow of information, marketing problems, and failure of technology transfer.

Poor flow of information and lack of technical assistance

Marginalisation of rural areas has created a status of endemic poverty in which the majority of smallholders are immersed and consequently has also restricted farmers' access to technical assistance. In some cases for example, potential productivity of local sheep is hindered by traditional flock management practices such as continuous mating seasons, breeding of closely related animals, absence of weaning, and selection criteria based in phenotypical aspects that might mislead selection for productivity. Furthermore, high incidence of illiteracy in rural areas exacerbates the poor flow of information to some smallholder sheep farmers, and the opportunity for them to learn by direct observation of improvements in other farms or other regions is limited. The indigenous knowledge and field expertise that have developed through decades of farming may be insufficient when dealing with new issues such as population pressure, diminishing farming area, or environmental regulations. Marginalisation therefore positions smallholders in a condition where the lack of training and practice in decision-making makes them unable to cope satisfactorily with current issues. Consequently, smallholders are immersed in a lack of awareness of policies concerning agricultural, marketing or ecological issues, which prevents them from participating in decision-making at regional level.

Market problems

The marginalisation of the rural environment also hampers market development for sheep smallholders. Isolated smallholdings have difficulty in accessing markets and as a result they are forced to trade their products on disadvantageous terms via middlemen. Buying sheep in bulk, rather than by being individually weighed is a common practice through which the middleman profits at the expense of the producer (Ordóñez *et al.*, 1990; Nuncio-Ochoa *et al.*, 2001). The high demand for sheep meat in Mexico has not been able to stimulate the development of a market infrastructure in which smallholders can place their produce effectively. Seasonal availability of foraging resources also provokes an irregular supply of sheep products from small-size farms throughout the year, discouraging the creation of markets. Thus a vicious circle prevails in which the lack of market access not only affects the trading of farmers' goods, but also affects the costs and supply of other inputs, production services and technical assistance.

Low technology transfer

The small ruminant sector in developing countries has been subject to the introduction of technology and practices designed for intensive systems in developed countries without prior consideration of their suitability to the local environment, and without acknowledging existing socio-economic structures (Galina and Russell, 1994; Morand-Fehr and Boyazoglu, 1999). Mexico has not been exempt from such phenomena, and agricultural advisors, technicians and policy makers in the sheep sector have engaged most of their efforts in consolidating a sheep industry based on intensive production. Much of the technology and practices to improve sheep farming have been directed to the maximisation of the biological or financial outputs of the system, thus being adopted only by a minority of large commercial enterprises and not by the majority of smallholders. Government assistance to the sheep sector has focused on subsidies for the purchase of improved breeding livestock, introduced forage seeds, and other commodities such as electric fencing, machinery and equipment (SAGARPA, 2000a). The 2000 annual report of the subsidies program (SAGARPA, 2000b) showed that during the last four years of its implementation the number of participating farmers decreased by 40%. The report casts doubts on the viability of the program, since despite the subsidies, farmers did not have the ability to devote cash to it. Furthermore, it was recognised that the lack of adequate technical assistance as well as the absence of strong markets for livestock products dissuaded the addition of more farmers to this program.

Policy makers have believed that the future of the sheep industry relies on the intensification of the production systems and have disregarded the fact that if the smallholders' objectives are not purely market-orientated, the level of adoption of "financial maximising" technologies will be almost null. As highlighted by Thornton and Herrero (2001) and Chambers *et al.* (1989), the failure of technology adoption by farm households is through lack of understanding of farmers' objectives and goals. An effective design of strategies to address sheep smallholders should consider the non-financial values that the household attaches to sheep. Both economic and non-economic goals coexist in the farmer's mind, and they are not mutually exclusive (Solano *et al.*, 2001).

Both the varied role of sheep in the functioning of the smallholder system and their value other than as solely commercial assets for the household have been previously acknowledged (Pedraza and Perezgrovas-Garza, 1991; Arriaga-Jordan *et al.*, 1997; Devendra, 2001). Thus, the same parameters and criteria that are used with specialised sheep farms cannot be extrapolated to smallholder systems. In commercial farms, the financial turnover of the enterprise is traditionally the ultimate indicator of the farm's performance. Such a criterion cannot be directly transferable to smallholder farms, since doing so would lead to an inadequate understanding of the real qualitative and quantitative performance of the system (Dalsgaard and Oficial, 1997; McDermott *et al.*, 1999), and would engender unawareness of the intangible contributions of sheep to the poor households.

Some of the scientific and technical knowledge developed in universities and research centres, particularly that related to sheep reproduction and nutrition, has failed at the moment of being transferred to smallholder farms. In this context, one of the reasons for this failure is that under smallholder systems' feeding regimes under-nutrition states can easily be generated. Consequently, reproductive performance or utilisation of nutrients can be altered, and trials that have proved successful at an experimental level affected (Morand-Fehr and Boyazoglu, 1999). Unfortunately, even technology that has seemed to be directly applicable to the conditions of smallholder systems has failed to be transferable (Galina and Russell, 1994). The socio-cultural elements of the household appear to be more of an obstacle for the adoption of technology than the scientific paradigm that directs the production of such technology.

Neither policy making nor scientific knowledge for agriculture in Mexico have had a positive enough impact on sheep smallholder systems to boost their development. There has been a lack of understanding that has jeopardised the potential of these farming systems to contribute to the Mexican agricultural sector, and ignored their role as a means of enhancing rural development and improving households' quality of life. Agricultural and environmental policies, as well as new technology and managerial practices that are targeted to smallholder farmers, should be designed and produced with consideration of the relationships that emerge between the prevailing social, cultural, economic and ecological elements of the smallholding.

2.4 Characterisation of smallholder sheep farming systems in Mexico

Through characterising a farming system, the boundaries of the system are identified and guidelines for identifying problems, constraints and opportunities can be established. Characterisation helps to identify the relationship between households' features and their environment, and facilitate the understanding of the way households make decisions about their farm management. The identification of prevailing differences among sheep smallholder systems can help to improve policy making and direct scientific production towards higher levels of technology adoption (Chambers *et al.*, 1989; Dent *et al.*, 1994).

As has been mentioned, the conception of smallholding lies on the role of the family household as both the entity responsible for and the final beneficiary of farming activities. Therefore, sheep smallholder systems can include a wide combination of social, economic and environmental variables. Following the framework of McDermott *et al.* (1999) to analyse the economics of smallholder livestock systems, a typology to characterise sheep smallholder systems can be defined according to both the level of intensification of the sheep farming activities and the proportion of household income generated by sheep production. In such a way, the combination of both classification criteria for sheep farming systems defines the typology of smallholdings. Thus, smallholder sheep farmers might be conceptualised with the interaction of various degrees of importance and intensification of the sheep element within the household.

Characterisation means that both common and unique features can be spotted across the wide variety of smallholder systems, from market- to subsistence-orientated, and from pastoral to intensive systems. Fully understanding of the role that the sheep element plays within the smallholding is essential if erratic guidelines or technical advice that can have either a null or negative effect on the household are to be avoided. For instance, epidemic diseases will have a larger impact if sheep are raised extensively and graze on communally owned land, whereas ruminal acidosis or foot-related diseases will predominate in stall-feeding systems. Productivity, farming practices, and management of the surrounding environment will differ across the full spectrum of the smallholding typology.

Figure 2-2 illustrates McDermott's (1999) typology applied to the characterisation of three local smallholder sheep farming systems in Mexico. In case 1, Nuncio-Ochoa *et al.* (2001) reported the characterisation of sheep systems in the southern state of Tabasco. In this study, sheep farmers were grouped in three economic strata (high, medium and low). High-stratum farmers were shown to undertake commercially-orientated sheep farming that was complementary to cattle farming and with a strong use of external inputs. The medium- and low-strata farmers corresponded to systems with diversified traditional farming systems. The main difference between the medium- and low-strata groups was the significance of off-farm activities on the household income. Scarce resources for low-strata farmers forced them to undertake paid labour in non-agricultural activities. The study also showed the importance of the farms' geographic location on the definition of the farmers' economic stratum. In case 2, Ruíz *et al.* (1991) characterised the sheep farming system within one municipality of the state of Veracruz. The study showed the existence of two groups of smallholdings both with sheep farming activities with low technical inputs. Sheep farming was the main source of income for the first group, whilst for the second group sheep production was complementary to other agricultural activities and consequently farmers handled smaller flocks. Finally, case 3 is reported by Arriaga-Jordan *et al.* (1997) with the characterisation of smallholder agricultural systems of a municipality in the temperate area west of Mexico City. Farmers were grouped according to two geographical zones, high and low. In both zones, sheep were integrated with other cropping activities and sheep farming represented a means to capitalise households' surpluses. The importance of sheep within the household system was dependant on both grazing resource availability and maize productivity. Highland farmers had access to grazing areas that allowed them to have larger flocks, whereas higher maize productivity in lowland farms meant that surpluses were allocated to pig feeding. This situation, along with low availability of grazing area in the lowlands, placed sheep as an element with relatively lower importance within the lowland system compared to the highland one.

The first directive for the policy maker and scientist with regard to the improvement of sheep productivity in smallholdings is to locate each particular system in this typology. Given that smallholder systems are frequently labelled as simply extensive or subsistence-orientated systems, this typology could help to avoid misconceptions over the type of system. This is particularly important where a system is diverse, since different levels of intensification might be exerted across the agricultural activities of the household. This variability in the degree of intensification of activities can be illustrated by the role of extensive sheep grazing in commercial rubber plantations as a means of diversifying farmers' incomes (Ruíz *et al.*, 1991), and the market-orientated sheep farming with the use of traditional mobile pens for manuring maize fields (Losada *et al.*, 1996).

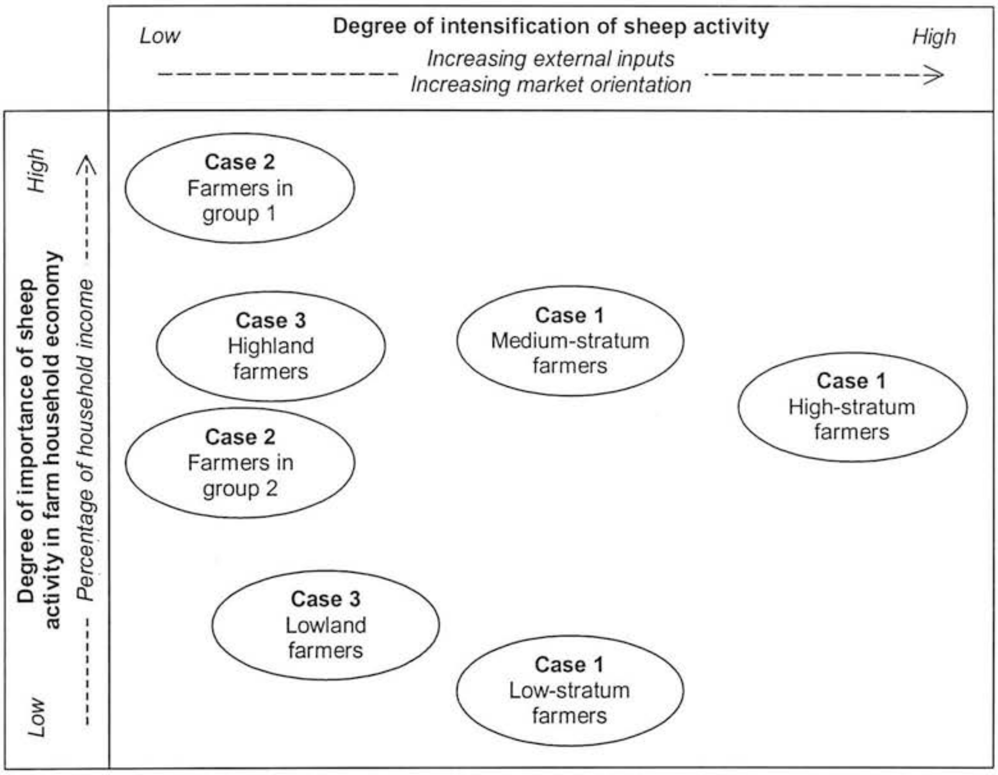

Figure 2-2 Typology for the characterisation of smallholder sheep farming systems in Mexico based on McDermott (1999). See text for explanation of Case 1, 2 and 3.

The significance of characterising a farming system in order to improve the way it is perceived and understood has been mentioned. Furthermore, it is important to point out that such characterisation will be more effective if it does not only describe the way a household's available resources are utilised, but it also includes an understanding of the managerial capacity of the household and its interactions within the socio-economic environment (Solano *et al.*, 2000). There are some important factors that influence this relationship between resource utilisation and the socio-economic environment of the smallholding. Three of these factors are of particular relevance to the managerial process of the household: i) differentiation between market- and subsistence-orientated production, ii) opportunity for diversification and risk aversion, and iii) access to communal resources.

2.4.1 Subsistence- and market-orientated systems

The differentiation between subsistence- and market-orientated smallholdings can be misleading regarding the perception of the system. Even if the sheep element of the farming system is not managed with a commercial purpose, it has some degree of influence on the system's economy. As part of the smallholding system, it is difficult to isolate sheep farming inputs and outputs from the rest of the household's activities (González *et al.*, 1996; McDermott *et al.*, 1999). The presence of sheep on arable plots for example, can have a positive effect on soil fertility and weed control. In addition, sheep make an economic utilisation of non-marketable crop residues that are then converted into value-added products (Devendra, 2001). In some smallholdings, sheep represent a means of capitalising surpluses and savings by, for example, the purchase of lambs for fattening or breeding ewes. On the other hand, available time for off-farm labour is constrained by the time spent in shepherding or other sheep keeping activities.

Although the immediate target of smallholder systems focuses on providing primary needs, in many cases this is attained through the implementation of some market-orientated activities. Whether in the form of weaned lambs, wool garments, or cooked meat, the smallholding finds a niche in the agricultural market. Thus, the study of sheep smallholder systems requires an approach that is able to describe quantitatively and qualitatively each facet of the household's economic dynamics. Whether subsistence- or market-orientated, the economic significance of sheep within the system must be recognised and sensibly assessed. Such economic importance depends on the way the household allocates resources and effort to the sheep farming activity, and the degree of contribution that the family assigns to it in meeting financial needs. External factors such as climate, forage availability, market power and opportunity cost of temporary off-farm labour influence this contributing role of the sheep element within the smallholding's economy.

2.4.2 Risk management and diversification of the system

A very important characteristic to be included in the analysis of sheep smallholder systems is the position that households take when facing risk. A farmer's attitude towards risk is fundamentally linked to both the intensification of the system and its degree of market-orientation. The flexibility of the ex ante and the ex post coping strategies that the household exerts to deal with risk is constrained either by higher intensification or commercial orientation of the system. If the household is able to increase market-orientated activities it might also have to face the uncertainty of regularly accessing a sufficient supply of cheap raw materials for feed as well as the uncertainty of a consistent demand for their products (Udo, 1997). Hence, attitude towards risk directly affects the type of technical assistance that farmers might demand as well as their willingness to adopt new technologies. In general terms, the more market orientated the system is, the greater its need for decision-making tools and the greater the demand for specialised services (McDermott *et al.*, 1999). On the other hand, in less intensive systems, sheep might represent the means to capitalise assets within the household, which would therefore entail a risk-avoidance practice (Udo, 1997). Avoiding risk jeopardises the potential to participate in the agricultural market, and therefore constrains the possibility of developing a more commercially-driven activity (FAO, 2000).

As a consequence of the above-stated reasons, it is of utmost importance to consider the trade-offs between risk avoidance strategies and the implementation of stronger commercial activities. Diversification of agricultural activities is a strategy that the household can make use of in order to avoid risk. Much of the traditional knowledge that smallholders have developed is directed to cope with risk (Netting, 1993). When dependence on the environment is high, the system becomes more flexible and the decision-making process that the household exerts is made in a shorter time-scale, maybe even on a daily basis. However, the external environment can also be the great weakness of such a system when the ability to cope with climatic risk is affected either by market conditions, price structures or production costs (Eakin, 2000). If an occasional event is beyond the ability for adjustment, the household may resort to emergency measures such as selling off ewes or lambs for cash to support their families. The household capacity to bear risk will depend on how close it is to the survival threshold (McDermott *et al.*, 1999). As a result, if the farmer were forced to sell off the household's assets, the family welfare could be compromised, especially if family members were forced to abandon their agricultural practices and seek labour, migrating either to urban centres or to a more developed country (in the case of Mexico, the United States).

2.4.3 Access to communal resources

Land tenure is another relevant factor that has an effect on the strategy that smallholdings adopt to manage their resources. Land tenure form in Mexico is organised in farmers' organisations or "ejidos", in which farmer members have usufruct rights but not ownership rights over land parcels. In addition, there is also the existence of several smallholdings with access to communal land. According to the 1991 Mexican agricultural census (INEGI, 1994), more than 50% of the total agricultural production units were under some form of communal tenure. Thus, a very common practice found in smallholder sheep farming systems is that flocks are herded in grazing areas that are communally owned.

Unfortunately, communal land tenure in Mexico embraces a legal ambiguity of property rights (Cymet, 1992). Such ambiguity has generated restricted access to institutional credits along with a lack of integrated management of the communal land (Thoms and Betters, 1998; De Janvry and Sadoulet, 2001). This long-standing state of affairs in communal land tenure has brought about a lack of incentive to control stocking rates and/or to improve the status of communal resources. In 1992, reforms to the federal law of land tenure (Mexican Constitution's Article 27) permitted the privatisation of communal lands and smallholdings that were under the "ejido" tenure form. These reforms modified property rights to sell and rent land as a means of enhancing market opportunities and productive development for the agricultural sector (Cebreros, 1991). Contrary positions to this policy (e.g. Calva, 1994; Galindo, 1997) have called attention to the threat upon the survival of smallholder systems that such reforms can bring about. The free market of "ejido" land allows foreign corporations to own and lease land, transforming smallholders into a waged labour force (Randall, 1996; Diego, 1997).

The scenario described above raises new conditions and challenges to be included in the analysis of smallholder sheep farming systems. Land tenure strongly determines access to grazing resources, whether they come from grazing areas or from agricultural by-products. It also influences farmers' decision-making and generates opportunity costs for other non-agricultural activities and off-farm labour. Under tenure insecurity circumstances, sheep might represent an important means of capitalising the household's assets. In addition, land access might be the limiting factor for a more market-orientated sheep production.

2.5 Potential features of smallholder sheep farming systems for their development

The stagnation in the economic development of smallholder sheep farming systems is evidence of the complexity and paradoxes of Mexican agriculture. The low economic impact that these systems exert on the agricultural GDP has meant that the significance of sheep production in smallholdings has remained unrecognised. Current economic, market and land tenure policies that the country is undertaking drive the necessity to develop agricultural production systems that are not only able to satisfy market demands, but are also able to enhance rural livelihoods and to advance in a sustainable form. Thus, a complete understanding of the characteristics and dynamics of smallholder sheep farming systems can help to unveil the potential role that such systems can have as participants in the development and enhancement of life quality in rural areas. In the following section some characteristics of these systems that provide an opportunity for development are highlighted according to ecological, economic and social issues.

2.5.1 Features relevant to ecological elements

Some decades ago the green revolution impacted on Mexico with increased industrialization of agriculture, intensive commercial production and the expansion of permanent monoculture cultivation, whereby chemical fertilisers and pesticides were widely used. The impact of agricultural activities on the environment has been recognised relatively recently and agricultural policies in Mexico are now aiming to assist in the development of more environmentally friendly agricultural practices. The Federal Government has outlined in the National Plan for Development 2001-2006 (SAGADERPA, 2001) the need to direct the development of Mexican agriculture through sustainable agricultural practices. Under this compelling scenario, smallholder sheep production systems stand as a potential means of enhancing the sustainability of agricultural production in Mexico. Such a scenario could be attained through the exploitation of two important characteristics that these systems possess: i) integration of diverse agricultural activities and, ii) use of traditional grazing practices.

The smallholder can benefit from the integrated use of natural resources through the diversification of farming activities and produce an environmentally friendly form of agriculture. Traditional smallholder agriculture in Mexico has been sustained on the diversification of farming activities through practices such as multiple cropping, diverse home gardens, or crop growing in "chinampas" or wetlands (Wilken, 1987; Gliessman, 1991; Dalsgaard and Oficial, 1997). The integration of sheep farming activities with these kinds of cropping activities plays a key role in the cycling of nutrients, whether by producing manure for fertilising or by consuming agricultural by-products.

Several examples of the role of sheep as a means of cycling nutrients in smallholder systems have been reported. Of special interest are the two most common feeding practices found in smallholder sheep farming systems after grazing. The first one is the use of dry stubble as feeding resource in the dry season once maize has been harvested (Castillo *et al.*, 1990; Arbiza *et al.*, 1991). The second one is the undertaking of labour-intensive practices to improve soil fertility with the use of mobile sheep pens that are rotated across the cropping area (Perezgrovas-Garza and Pedraza, 1990; Losada *et al.*, 1996; Zaragoza and Rodríguez, 1997;). Additionally, another example of integrated smallholder production is the inclusion of sheep in agroforestry systems, either applying traditional knowledge in the use of fodder from trees as cut-and-carry feeding (Nahed *et al.*, 1998; Nuncio-Ochoa *et al.*, 2001) or grazing in specialised cropland such as orange fields (Pérez-Amaro, 2001) or rubber plantations (Ruíz *et al.*, 1991).

In addition, the inclusion of sheep in integrated systems represents a much less severe pollution threat than rearing other forms of livestock production due to the reduced amount of effluent from animal waste. Although these actions carry great weight from a conservationist point of view, it is important to highlight that an integrated management of resources cannot only bring environmental benefits, but can also function as a productive and profitable activity (Dalsgaard and Oficial, 1997; Altieri, 2000).

Regarding the importance of traditional sheep grazing practices, it has been acknowledge that grazing plays a key role in maintaining semi-natural habitats and landscapes in a steady state (Bignal and McCracken, 1996; Kuiters, 1998; El Aich and Waterhouse, 1999). Grazing impedes the development of shrubland, it creates regeneration niches by trampling and ground disturbance, it prevents the spreading of fire by removing accumulated plant material, and lastly it maintains dynamic processes in fragmented landscapes (Mitchell and Kirby, 1990; Fischer *et al.*, 1996; Gómez-Gutiérrez *et al.*, 1998; El Aich and Waterhouse, 1999). Unfortunately, inappropriate grazing practices in Mexico have led to land degradation and loss of biodiversity, especially in areas with communal property, where negative consequences might be exacerbated. It is not surprising then that sheep are regarded as a threat to environment conservation, and that environmentalists view grazing activities in semi-natural and natural landscapes as intrinsically damaging. However, the role of well-managed grazing systems as a tool for ecosystem conservation has also been favourably acknowledged and the subject of recognition in other regions, such as the European Union through the Common Agricultural Policy (Waters, 1994). In these countries, traditional grazing in low-intensity farming systems is valued as a key process in the ecosystem dynamics, and it is considered to help in the recovery or maintenance of marginal (Gómez-Gutiérrez *et al.*, 1998), semi-natural (Bignal, 1998) and virtually natural landscapes (Kuiters, 1998).

Therefore, it is under the scenario of adequate traditional practices that sheep grazing in Mexico can bring in environmentally orientated agricultural production. For instance, it is estimated that 95% of the national sheep population is Criollo (Alvarez, 1995; Sánchez del Real and Martínez, 1998). This animal is well acclimatised to the environmental conditions of the country and is able to survive in areas where other pure bred sheep might not. As a result, the Criollo sheep has adapted to make use of the native vegetation. The introduction of improved sheep breeds is usually associated with the replacement of native vegetation by introduced grass species, which affects the landscape and the habitat structure. Thus, there is a clear association between both the conservation of the native vegetation structure and biodiversity of plant habitats and the continued raising of native sheep flocks by farmers.

In addition, shepherding is still practiced in Mexico as an essential component of traditional grazing practices. It is usually one of the members of the household who undertakes the role of shepherd and spends the whole day looking after the sheep flock and driving it to areas of better vegetation. Shepherding has been recognised as a valuable activity for managing extensive grazing systems in helping to alleviate inappropriate distribution of animals that generate overgrazing (Fischer *et al.*, 1996; El Aich and Waterhouse, 1999). Moreover, sheep grazing activities in the majority of the country take place in response to seasonal conditions. Forage seasonality makes grazing practices highly active during the rainy season, and very restricted during the dry season. Across the country, the dry season corresponds to the harvesting season of many crops, creating alternative feeding sources for livestock and helping to reduce grazing pressure on the vegetation. Smallholder sheep farming systems have been carrying out these traditional aspects of sheep grazing management for generations. They have created a rational grazing method that to a certain extent functions in harmony with environmental conservation principles. Unquestionably, the fact that overgrazing may occur in these systems cannot be overlooked, especially given that its damaging effects through desertification and disruption of habitats have been identified (e.g. (Alvarez-Cardenas *et al.*, 2000; Manzano *et al.*, 2000)). However, it is important to highlight that conservational issues concerned with sheep production systems are very often beyond a mere environmental or biological context. Such issues are deeply immersed in complex social and political frameworks. Sheep farmers are often blamed for causing environmental damage, when in fact they try to adjust to economic or political events over which they have little or no control.

2.5.2 Features relevant to social welfare

The FAO in its 2000 report "The State of Food and Agriculture" (FAO, 2000) stated the need to rescue the most destitute peasant farmer populations from exclusion and poverty through "developing their food production capacity both to help them improve their nutritional status and to create employment and income for the poorer groups". In this context, it is important to recognize the potential contribution of sheep to smallholder farms and livelihoods in rural areas. It has been mentioned that sheep play an integral role within smallholder agricultural systems, and therefore, as long as sheep production positively influences the smallholding system, it has the capability to stand as a vehicle for rural development.

Whilst large-scale commercial production systems are of little benefit to local farmers in developing countries (Udo, 1997), improvement of smallholder agricultural systems can have a positive impact on the welfare of rural families, thus representing a key strategy for poverty reduction (Dixon *et al.*, 2001). Sheep contribute significantly to the diversification of the household's economy since they can use a variety of marginal land resources. Their low demand for labour and capital as compared to cattle ensures that small ruminants contribute more to economic diversification than other livestock activities (Devendra, 1981; El Aich and Waterhouse, 1999). In many cases sheep represent the ultimate phase in the monetary dynamics of the household economy, since they are used either as a saving source or for capital building (González *et al.*, 1996; Zaragoza and Rodríguez, 1997).

The social role that sheep farming has is not constrained to economic or monetary issues. As is underlined by Lukefahr and Preston (1999), the utilisation or preservation of traditional animal production practices keeps indigenous knowledge and social values in farming communities alive. It should be stressed that the reasons why farmers decide to keep sheep are usually influenced by family traditions and local customs. Perezgrovas-Garza and Pedraza (1990), Farrera and Perezgrovas-Garza (1997) and Zaragoza and Rodríguez (1997) have described the function of Criollo sheep within the indigenous communities of the highlands in the state of Chiapas. In this region, the role of sheep goes beyond mere economic values, and its development is surrounded by religious beliefs. Sheep meat is not consumed here, but the household benefits from the use of wool for making traditional garments and manure for the fertilisation of crop plots.

Sheep keeping and shepherding are undertaken by the household's members and can thus be of particular importance as a source for family labour in areas where environmental conditions make the widespread practice of other agricultural activity impossible. Furthermore, even in rural areas where labour can be a surplus, sheep keeping represents an economic activity that does not require land ownership. If sheep farming becomes a rewarding activity for smallholder farmers it might help to enhance rural living and to ease migration to urban centres in search of job opportunities.

Sheep meat does not have an important impact in improving the nutritional status of the household family. The high price that cooked meat ("barbacoa") receives in the market makes on-farm consumption difficult to afford, although such practice can be common in some households (e.g. Ordóñez *et al.*, 1990; Losada *et al.*, 1996). Although sheep meat is not a regular component of the household diet, sheep keeping is associated with festivities, family celebrations and social obligations. According to Sarmiento *et al.* (1991), for indigenous groups where sheep meat is not consumed for religious beliefs, ewe's milk represents the alternative to improve the protein consumption of the household.

2.5.3 Features relevant to globalisation of agricultural markets

Agriculture in Mexico has undergone profound transformations as a result of structural changes in the national economic policy. The Mexican government has promoted land privatisation and deregulation of agricultural markets, with the pinnacle in 1994 of the implementation of the North American Free Trade Agreement (NAFTA). Subsidies for agricultural production and marketing have been dramatically reduced in the last decade, and the vulnerability of small-scale farms has increased with the withdrawal of subsidies in the production and marketing of agricultural commodities (De Janvry *et al.*, 1995; Eakin, 2000). Smallholder farms that lack access to strong markets or agribusiness corporations have been seriously affected, which has been aggravated by the fact that domestic production has faced unfair competition against products imported at much cheaper prices.

In 1988 the Ministry of Commerce decreed a free market for sheep imports, with a consequent massive entrance of New Zealand, Australian and

American frozen sheep carcasses. The inability of the domestic production to supply the high demand in the country gave rise to an average of 52% of the total sheep meat consumed being imported during the last decade (SAGAR, 2000). Such imports have represented a big challenge to large market-orientated farms with high economies of scale, intensive production systems, use of grains for feeding, and access to formal markets. Furthermore, the import of breeding livestock has also dramatically increased and specialised commercial farms have acquired stock from Australia and New Zealand. Unfortunately, the overall impact of such imports has not been completely positive, due to a lack of rigorous quality control of the imported animals and poor adaptability of the latter to the Mexican environment (Bañuelos *et al.*, 1997).

Trade liberalization and political reforms have seriously affected smallholder systems through a sharp decline in domestic prices of basic agricultural products (maize, milk, beef). However, some evidence suggests that the sheep sector has been able to endure the restricted development that other sectors of smallholder agriculture have faced (Martínez-Rojas, 1991; Arteaga, 2000; Nuncio-Ochoa *et al.*, 2001). The primary reason for this is that even though cheap imports have affected mutton and lamb meat prices in the formal market, the informal chain of marketing that traditional smallholding farmers take has, to an extent, isolated them from such global competition. It should also be considered that the kind of meat that is produced by traditional farming is different to the frozen carcasses that are imported. The former is subject to higher demand in the domestic market. As long as the Mexican taste remains loyal to the consumption of "barbacoa", the committed "barbacoa" maker will continue to look for the meat quality that the traditional smallholder production system delivers: meat from mature animals, with considerable collagen deposits in muscles, and which have been grazing native grasslands and herbs. In this context, sheep raised within traditional smallholder systems will be able to maintain a niche in the market. Thus, with a permanent demand for the product, the characteristics of smallholder systems have a potential advantage in competing with large-scale sheep production. Smallholder systems have the chance to spread risk through diversification and integration of farming activities, with low economies of scale and the use of household labour and natural resources as a capital substitute.

The transition towards a more market-oriented agricultural products is seen as a crucial step in rural economic development and poverty reduction (Dixon *et al.*, 2001). Attaining this however, should not exclude smallholder farming systems from actively participating in the economic operation of rural life. The potential of smallholder sheep farming systems as a valid economic activity should not be set aside by the current political and economic framework. As small-scale production is the only type of sheep farming that is currently increasing in large parts of the world (Boutonnet, 1999), Mexican smallholder sheep systems should not be left behind nor deprived of their potential participation in rural economic growth.

2.6 Vision for the development of research applied to smallholder sheep farming systems in Mexico

In previous sections of this chapter, some of the most relevant characteristics that define smallholder sheep farming systems in Mexico have been described; factors that have hindered sheep systems' development along with considerations of their potential for future development. In order to unveil such potential it is necessary to have a full understanding of smallholder sheep systems' characteristics in the areas of applied research, technology transfer, extension services and policy making. The effectiveness of these enterprises requires an imaginative approach in the work of scientists, technicians, extension workers and policy makers, so that the full range of the smallholder sheep typology is considered in the search for solutions in a community or region. Thus, having a complete characterisation as a starting point, the objective is then to understand the real scope and impact of the solutions that can be proposed. The characterisation of smallholder sheep farming systems should help in the recognition of both traditional practices that prove to be effective, and activities that demand adjustments and guidelines to improve their management. The challenge is to identify to what extent it is feasible to force these systems towards what is conceived as sustainable development and economic growth, whilst concomitantly maintaining traditional practices within the households' social and cultural framework.

2.6.1 Vision for research in agricultural systems

It is therefore necessary to re-orientate the agenda in sheep science towards the production of applied research that is able to respond to the reality of the most widespread system of sheep production in Mexico: smallholder systems. Such an agenda should underline the inclusion of social, environmental, technological and economic aspects of smallholder systems. Above all, it should be based on priorities and concerns expressed by the farmers, adopting new approaches that embrace the principles of agricultural systems approaches.

A systems approach can be described as "the systematic and quantitative analysis of agricultural systems, and the synthesis of comprehensive, functional concepts of them" (Kropff *et al.*, 2001). It aims to produce analysis tools to improve the utilisation of resources available within the farm environment and assist farmers in their decision-making process through a multidisciplinary and holistic framework. The remainder of this section will assess how smallholder sheep farming systems in Mexico can benefit from research based on the agricultural systems approach. As has been stressed, conventional approaches (reductionism) that study smallholder sheep farming systems lack a full understanding of the dynamics of their surrounding resources and the rationale of the household managing them. Systems approaches have been successful in better understanding the circumstances under which farmers operate, and promoting their direct involvement in data generation, evaluation, and selection of technology (Collinson, 2001). A farming systems approach makes use of different tools such as biological simulation modelling, Geographical Information Systems (GIS), economic models, and mathematical optimisation techniques. However, it is not the use of such specific tools where the relevance of systems approaches lie, but the framework under which they are developed and applied: participatory and on-farm research.

2.6.2 Participatory techniques

Participatory research includes farmers' perceptions, values and goals drawing farmers into the problem-identification process and improving the household's involvement in the research process (Chambers, 1997). Farmers' participation has positive effects on applied research by adding indigenous knowledge to scientific knowledge. Such an exchange of information seeks to improve agricultural practices and create a better framework for technology adoption (Okali *et al.*, 1994). The gap in knowledge and understanding about smallholder sheep farming systems stresses the need to apply participatory techniques to generate effective information to address their study.

Participatory approaches have, to some extent, been applied in the study of smallholder sheep farms in Mexico. Arriaga-Jordan *et al.* (1997) and Chavez-Mejia *et al.* (2001) carried out participatory research and on-farm experimentation to the reintroduction of traditional cultivation systems to enhance the agrodiversity in smallholdings of which sheep were an element. Camacho *et al.* (1999) and Nahed *et al.* (1998) applied the indigenous botanical classification of local trees to study their potential use as a fodder source for sheep feeding in the highlands of Chiapas. Finally, Loza-Arvizu (1998) used participatory techniques to improve management practices that had positive effects on fertility rate, daily weight gain of lambs and the prevalence of parasitic diseases in sheep smallholder farms.

2.6.3 Biological simulation modelling

Simulation models are useful tools for the ex-ante assessment of the dynamics of the biological elements that comprise an agricultural system. Effective modelling can identify and quantify the subtle but often highly significant interactions that occur between the various components of smallholder systems (Thornton and Herrero, 2001). Unfortunately, the majority of simulation models have been developed under conditions that do not match the reality of smallholder systems in developing countries. Castelan-Ortega *et al.* (2000) reported some of the drawbacks found in applying generic models to the environmental characteristics of agricultural smallholder systems in Mexico. Thus, although substantial development has been made in the modelling of sheep production processes, little effort has been put into the calibration and validation of them in Mexico, and specifically in the context of smallholder systems. Some advance was reported by González-Estrada *et al.* (2000) applying a ruminant performance model to a commercial flock.

The use of simulation models in smallholder systems represents a challenge for research due to the complex interactions that exist within the farm and the environment. In order to effectively use simulation modelling in Mexican sheep systems, it is essential to implement on-farm validation and calibration of existing models, or when necessary, to create new ones. As suggested by Thornton and Herrero (2001) it is important to develop a unifying framework for modelling assuming some degree of commonality (generic tools) in the behaviour of individuals, but also recognising the particular differences that can be found across the typology of the smallholder systems.

The validation or generation of simulation models applicable to the environmental conditions of Mexico requires an increased understanding of some of the biological processes that are an integral part of smallholder sheep farming systems. Of particular importance is advanced understanding of sheep grazing behaviour in natural and semi-natural habitats of Mexico and its effect on the vegetation dynamics. Furthermore, the forage value of many plant species has not been characterised, and there is an absence of information regarding the use of understorey vegetation in temperate regions, and the use of shrubs and trees as a fodder source in the tropics and arid zones (Camacho *et al.*, 1999; Ramirez, 1999). Research also needs to be focused on the interactions between sheep and crops in smallholder mixed systems. In this context, more information is needed about the role of sheep in nutrient cycling and their effects on the cultivation of maize, cash crops or traditional "milpa" systems[1]. In addition, nutrition science will have to develop nutritional standards for local sheep breeds based on the use of local forages and agricultural by-products (e.g. Arellano *et* al., 1993; Camacho *et al.*, 1999). The potential of local Criollo sheep and hair breed sheep will need better characterisation in terms of productive and reproductive performance trials (e.g. González, 1977; Galina *et al.*, 1996).

2.6.4 Geographical information systems

GIS are analytical tools with increasing recognition within agricultural system approaches. Through GIS-based tools it is possible to include the spatial arrangement of resources in regional-scale analyses to project, explore and predict agricultural land use (Stoorvogel and Antle, 2001). Comprehensive regional analyses can be attained by the integration of economic and simulation models within a GIS environment. The inclusion of spatial variables is of special interest when the study of sheep systems incorporates communal land issues, environmental conservation issues or extensive grazing resources management.

There is potential for the development of GIS-based tools in Mexico through the use of the information that the government is producing through its National Institute of Statistics and Geography (INEGI). This information

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[1] A small cultivated field of maize with legumes and/or other vegetables intercropped.

comprises digital maps, natural resources inventories, remotely-sensed data, and digital cadastral surveys in rural areas.

2.6.5 Multiple-criteria decision-making models

The search for the best management regimes for agricultural, ecological, economic and social resources is possible through the application of multiple-criteria decision-making models (MCDM) (Herrero *et al.*, 1999). Based on mathematical optimisation, MCDM models are an invaluable tool for scenario analyses and the impact assessment of ex post and ex ante changes in the agricultural system (Thornton and Herrero, 2001). MCDM models encompass holistic approaches with the use of simulation models and GIS to generate the input coefficients for the optimisation models. Moreover, the addition of economic models can bring in a more detailed representation of the household's economic dynamics and their effects on the social elements that intervene on the decision-making process. Thus, at a household level, a holistic assessment of changes in sheep management practices can be made and their effect on the smallholding's environment evaluated. Immediate and long-term effects of new technology adoption can be assessed in terms of: i) adjustments in productive and reproductive parameters; ii) quantitative and qualitative changes of feed sources; iii) labour availability and opportunity costs of both substitute agricultural practices and off-farm labour; iv) management intensity, investment appraisal and risk assessment; v) households' food security and social welfare; vi) infrastructure constraints and market accessibility; and, vii) trade-offs between sustainability and economic profitability.

In addition, relevant analyses at regional level can include: i) price control of agricultural production and inputs; ii) governmental programmes for technical assistance and subsidy analysis; iii) development of market centres and marketing channels; iv) management of communal land and stocking rates; v) climatic variability and effects on agricultural production and grazing resources; and, vi) grazing-exclusion areas for buffer zones in protected areas.

2.7 Extension services and policy making for the smallholder sheep farming systems in Mexico

2.7.1 Extension services

A knowledge-generating system needs to be efficiently linked to the continuous decision-making process of farmers. Improved information flow represents a powerful means of overcoming the marginalisation in which smallholder sheep farming systems are immersed. It is therefore of vital importance that the conceptualisation of these systems is of concern to both educational institutions and extension services bodies. The integration of research, education and extension can improve the overall performance of agricultural systems (Van Crowder and Anderson, 1996). Efforts must be made to improve the processes of technology transfer and poverty alleviation. These may be addressed through joint experiences of research centres, education institutions and extension workers. Such integration is key to the dissemination of the conceptualisation of smallholder sheep farming systems (Galina and Russell, 1994; Lukefahr and Preston, 1999). The role of the extension worker as an intermediary between scientist and farmers is essential to disseminate and promote the adoption of technology. The understanding of local farming and local farmers' decision-making gained through agricultural systems approaches is also a valuable resource for extension programming (Collinson, 2001).

In Mexico, there is some evidence of the success of governmental extension services in having a positive impact on sheep smallholder systems through the "GAVATT" program (Farmer Groups in Technology Transfer and Validation). Extension services can also play a fundamental role in the promotion of environmental protection and support for conservation policies enforcement. Major advances in other regions have been made in this area under the concept of "community conservation" (Infield and Adams, 1999), which tries to include local communities. Thus, the need for enhanced environmental protection leads again to the motivation for understanding the dynamics of social, cultural and economic elements of the smallholder system.

2.7.2 Policy-making

Agriculture is acknowledged as a key sector in pursuing poverty alleviation in rural areas of developing countries (Hoekman *et al.*, 2001). It is necessary that technology generation and transfer are superseded by an effective participation of the poor in the trading of agricultural goods through an adequate marketing structure (Hardaker, 1997). Currently, the Ministry of Agriculture has focused the direction of rural development through "productive, profitable and competitive" agricultural activities as stated in the plan for development of the agricultural sector 2001-2006 (SAGARPA, 2001). The plan also recognises the need to operate differentiated policies in response to the productive, social and economic heterogeneity of Mexican farming systems, thus underlining the importance of social welfare and environmental protection. Under this scenario, and in order to be included in the national project for development, smallholder systems need to improve their opportunities to participate in commercial activities.

In order to improve smallholder farms' participation in the marketing of sheep, government intervention is necessary in assisting the planning of organised regional markets (Devendra, 2001). Policy support and institutional commitment are also necessary in the price regulation of animals, carcasses and processed meat, and reducing the influence of middlemen (Nuncio-Ochoa *et al.*, 2001). Although according to the typology of smallholder sheep farming systems not all systems undertake market-orientated sheep production, the establishment of secure markets will benefit both smallholdings with commercial objectives, and those that have sheep as a complementary activity. In this context, caution should be taken in the implementation of policies targeted at smallholder systems, since as stated above, the same analysis criteria that are used with specialised commercial farms cannot be directly extrapolated to them.

In a previous section of this work, the potential importance of sheep within smallholder systems in the sustainable development of rural areas was discussed. Thus, it is through an integrated approach, rather than only through the isolated improvement of market-orientated activities, that smallholder sheep farming systems can have a positive impact on the improvement of rural quality of life. Project development and policy-making at a governmental level have an essential role in the consolidation of participatory and systemic approaches utilised in agricultural research and extension.

Special attention should be given to the Rome Declaration on World Food Security (FAO, 1996) in which Mexico was a participant. One of its objectives was to "strengthen local government institutions in rural areas and provide them with adequate resources, decision-making authority and mechanisms for grassroots participation". Thus, policies should give priority to projects that emphasize the participation and empowerment of subsistence-orientated smallholder systems in search of alternative strategies for development. The role of NGO's is recognised as important in this process (Udo, 1997).

The Mexican government should also look at the development of successful smallholder sheep farming systems in terms of their capacity to generate improvements in health status, employment, gender benefit and environmental conservation. The fulfilment of one or more of these benefits will be more likely to assist the process of rural development and poverty alleviation (Lukefahr and Preston, 1999).

Chapter 3

Characterisation of Grazing Systems of Coajomulco

3.1 Introduction

This chapter is divided in two main sections. The first section is concerned with the general description of the parish of Coajomulco and provides some background about the natural protected area. The latter part focuses on the process of gathering detailed information on the characteristics and functioning of the sheep farming system of Coajomulco. The characterisation of Coajomulco's sheep farming systems is focused on the animal element of the system. Thus, the methodology that is presented here was mainly concerned with the analysis of the animal variables that determined the

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Some of the contents of this chapter have been included in:

González-Estrada E., Palacios T.I., Fawcett R.H. and Herrero M. (2002) Landscape analysis of communal grazing resources in a Mexican montane forest: application of GIS techniques with a participatory approach to aid conservation strategies.

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patterns of forage consumption. To do so, the parameters that affect flock dynamics and the spatial distribution of grazing areas are investigated in this chapter.

3.2 The Parish of Coajomulco – "In the Midst of the Brambles"

3.2.1 Description of the study area

The parish of Coajomulco (meaning, in Nahuatl language, "In the Midst of the Brambles") is located in the central region of Mexico (19° 01′ N, 99° 16′ W). With an area of 6135 ha Coajomulco belongs to the municipality of Huitzilac, which is one of the 33 municipalities that comprise the state of Morelos. Coajomulco lies contiguous to Mexico City (see Figure 3-1). Since pre-hispanic times, the municipality of Huitzilac has been used as a resting point for the routes that link the country's capital with the sub-tropical region of Morelos. Nowadays, Huitzilac and its parishes, including Coajomulco, are crossed by the main roads that link Mexico City with the capital city of Morelos: Cuernavaca. The strategic location of Huitzilac has put it in the centre of national conservation plans to prevent the expansion of the urban centres of both Mexico City and Cuernavaca.

The municipality of Huitzilac lies along the central mountain range known as "eje volcánico transversal". As a result of the mountainous landscape, the altitude of Coajomulco varies between 2200 and 3200 m, generating a temperate sub-humid climate with annual precipitation averaging 1200 mm. Annual average temperature is 12°C, varying between 6°C and 18°C throughout the year. The annual rainfall and temperature distribution are shown in Figure 3-2. Montane forest is the principal vegetation type, with dominant tree species of *Pinus*, *Quercus*, *Abies* and *Alnus*.

3.2.2 Social background

According to the 2000 national population census (INEGI, 2001), Coajomulco's population was 1779 inhabitants. From this figure only 641 people were actively working. The population was predominantly of "nahua" indian origin (INI, 1998). Approximately 25 % of the working population was devoted to forestry and/or agriculture, as closeness to major cities has attracted younger generations to look for off-parish employment.

With the exception of family crop plots, land in Coajomulco is communally owned. Smallholder "campesino" agriculture is practised, with diverse agricultural production within the household system. Maize, black beans and faba beans are produced for self-consumption. In addition, some cash crops such as potato, spinach, radish, parsley and ornamental flowers are produced to be sold at the market in Cuernavaca. Where the size of the family plot allows it, larger commercial production of oats and potato takes place.

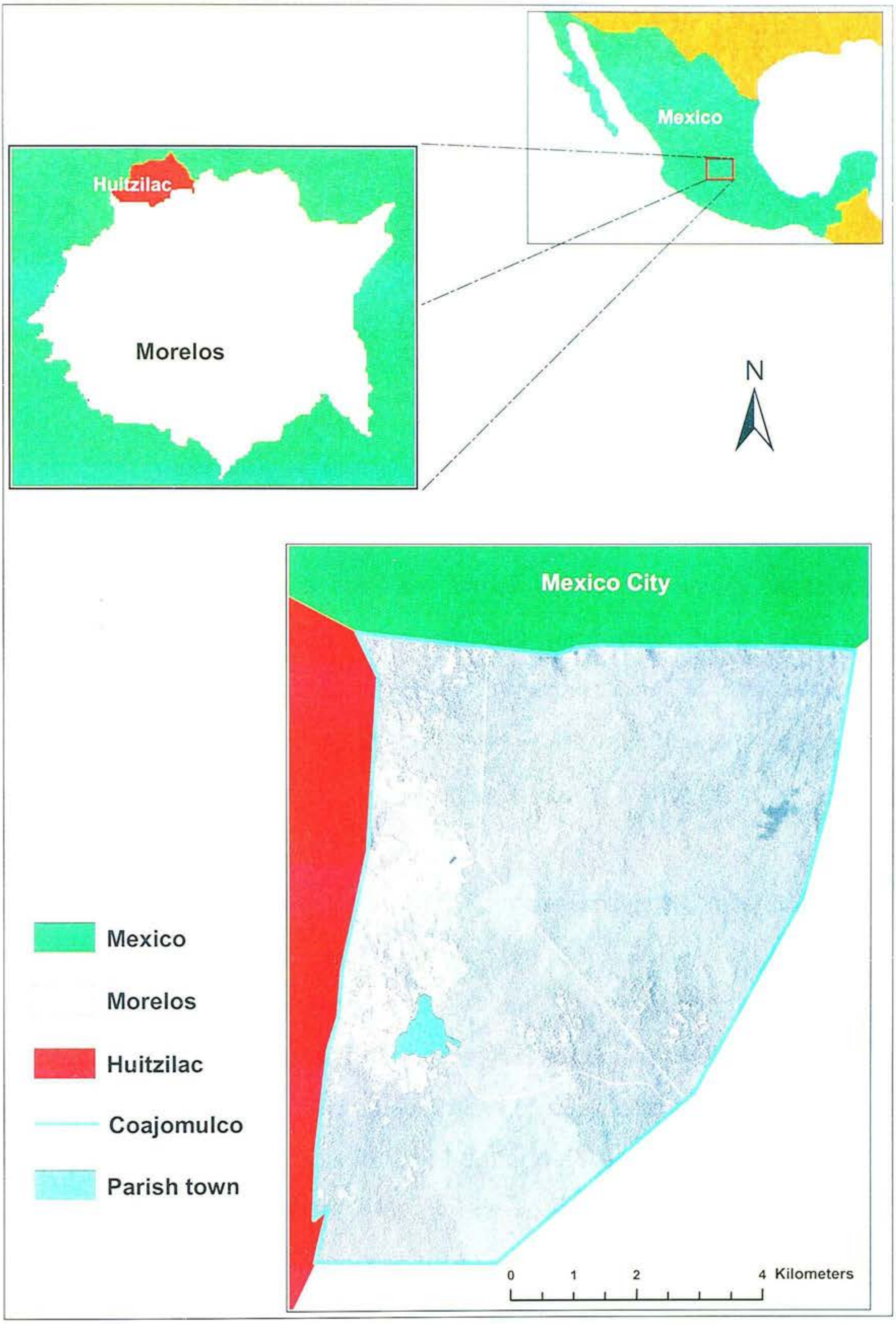

Figure 3-1 Geographical location of Coajomulco

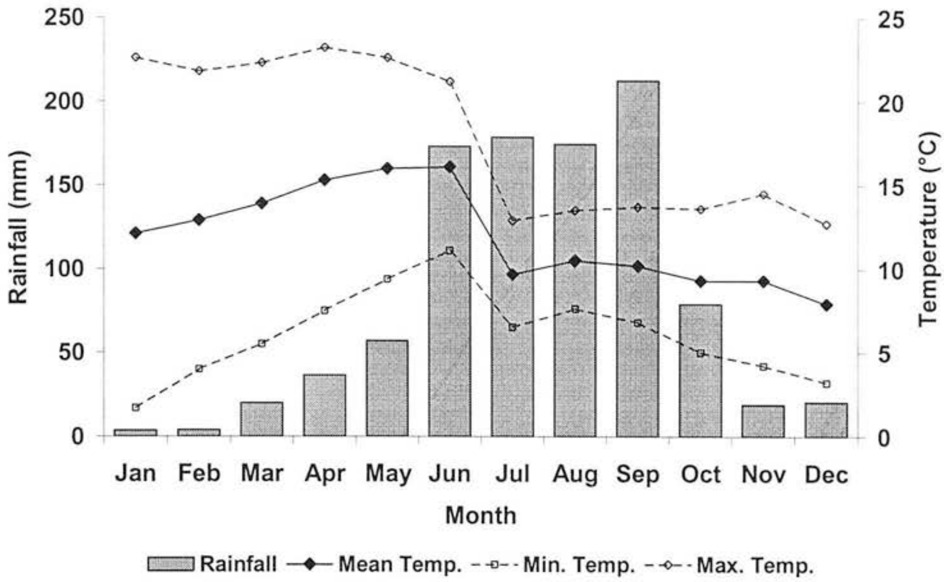

Figure 3-2 Rainfall and temperature distribution throughout the year in Coajomulco

The history of Coajomulco has been linked to the exploitation of forest resources. Small-scale timber and charcoal production have been an important source of income for Coajomulco's population. The prevalence of such activities however, came into decline when the area was categorised as protected area within the federal government's plan of National Parks.

3.2.3 Coajomulco as an integral part of "Corredor Biológico Chichinautzin"

From an ecological perspective, Huitzilac and its surroundings possess a high conservation value not only as a green belt as mentioned above, but also by the presence of endemic animal and plant species. In addition, Huitzilac's forest plays an important role in replenishing the water basins that supply water to Mexico City (SEDUE, 1989). As a consequence, in 1988 the federal government announced the creation of a protected area under the category of "Area de Protección de Flora y Fauna Silvestre y Acuática" (Protected Area for Wild and Water Plants and Animals). This category of protected area denotes the existence of a corridor that links two National Parks. The protected area in which Huitlizac lies was named as "Corredor Biológico Chichinautzin" after the largest volcano that dominates the region, joining the National Parks "Lagunas de Zempoala" on the west and "El Tepozteco" on the east.

The "Corredor Biológico Chichinatuzin" comprises an area of 37 000 ha (SEDUE, 1989), and the whole parish of Coajomulco is included within it. As a consequence, the creation of new cropping areas has been forbidden and all forest-based activities have been strictly regulated. Although sheep flocks can still have access to the woodland's communal grazing resources, a grazing exclusion zone was established to the northeast. The creation of this grazing exclusion area resulted in the inability of sheep farmers to make use of approximately 2600 ha; equalling 48% of Coajomulco's total communal grazing area. Figure 3-3 shows the location of the grazing exclusion area in relation to the parish town.

The creation of the protected area did not result in compensation payments for the local population. Coajomulco's local authorities obtained the right to grant special permits for tree-cutting and the extraction of non-timber products such as stone and soil. However, current regulations and controls are not sufficient to stop illegal logging, soil extraction, charcoal-making and the shepherding of flocks to the grazing-exclusion area.

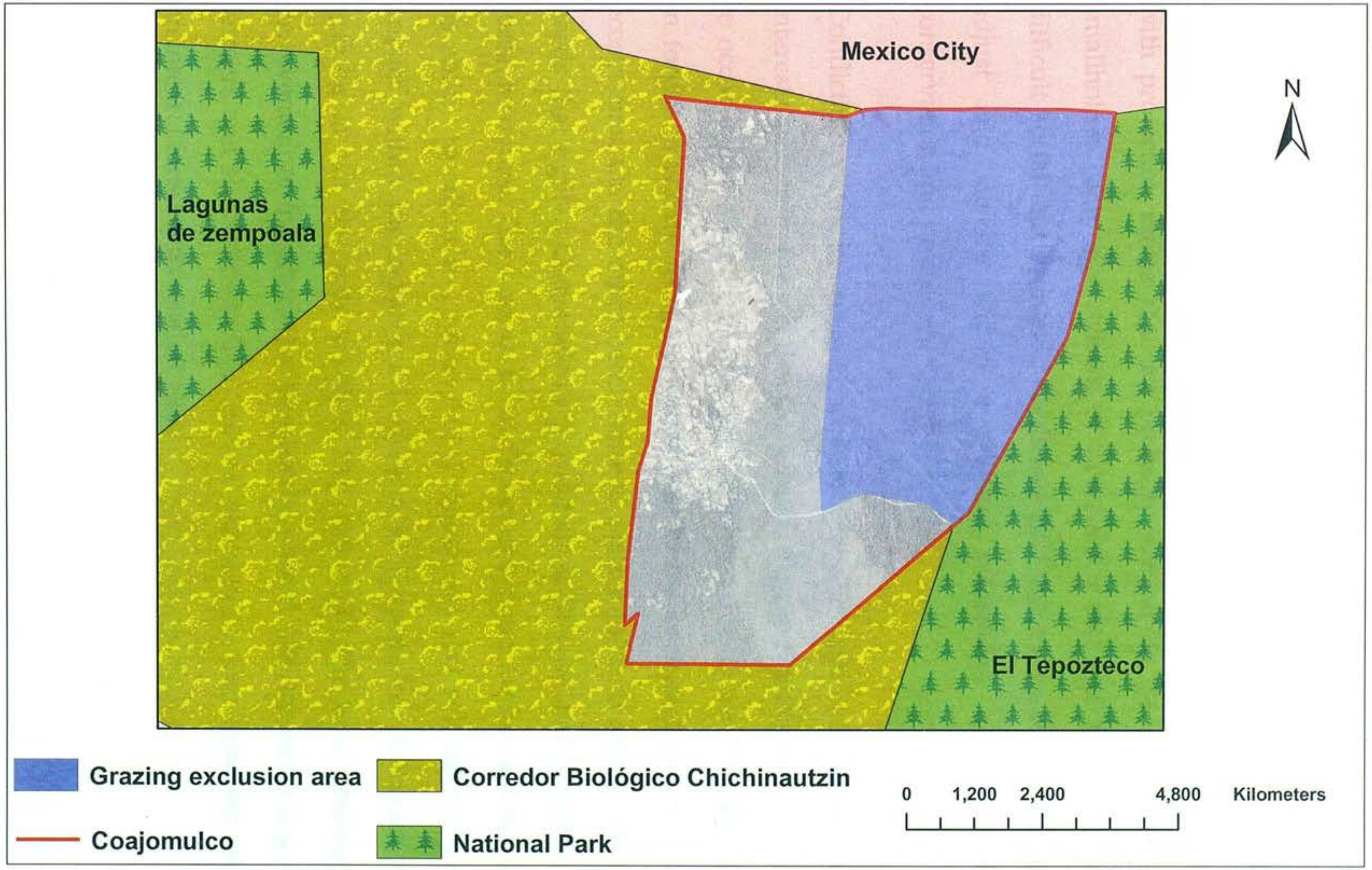

Figure 3-3 Coajomulco within the "Corredor Biológico Chichinautzin"

3.2.4 Relevant research issues

The conflict of conservation issues with agricultural activities in Coajomulco has brought a new challenge for the local population. This situation means that the farming community has been forced to harmonise its daily activities with protection issues that are probably low on its list of priorities. The smallholder campesino system of Coajomulco that has developed in the difficult social and economic conditions of Mexico's rural life has now to adjust and survive within a political framework of environmental conservation and protection.

Conflicting views between agricultural development and conservationist interests arise from the fact that Coajomulco's sheep farming has been forced to occur within a protected area. As mentioned in Chapter 2, sheep grazing in forests is widely recognise as a threat to the ecological balance of such ecosystems. On the other hand, there is the existence of ancient links and needs that tighten Coajomulco's population to the use and exploitation of forest resources. The survival of traditional sheep production will depend on its ability to adjust to environmental regulations and still have a positive impact within the agricultural systems of Coajomulco. Although sheep grazing is not the only problem that forests in the area undergo, the involvement of the actors that intensively interact with the forest (e.g. sheep farmers and shepherds in Coajomulco) represents a step forwards towards an integral forest conservation plan.

3.3 Methodological framework for the characterisation of Coajomulco smallholder sheep farming system

Following the basic representation of a grazing system, this section focuses on the gathering of the required information for quantifying the forage demand by Coajomulco's sheep flocks on temporal and spatial scales. A three tiered methodology was used to characterise the smallholder sheep farming systems of Coajomulco to facilitate the understanding of the dynamics of forage utilisation. This methodology was designed and undertaken applying the basic theory of Rapid Rural Appraisal (RRA) and Participatory Rural Appraisal (PRA) methods (World Resource Institute, 1990; Chambers, 1992; Kumar, 1993; Holland *et al.*, 1998). It comprised (1) a static survey, (2) the selection and monitoring of case studies, and (3) a participatory exercise. Data collection started in October 1999 and was carried out for 15 months.

3.3.1 Static survey

A questionnaire was designed based on guidelines suggested by Nichols (1991) and Quijandria (1994), and applied to all sheep farmers from the parish of Coajomulco. The questionnaire aimed to identify the characteristics of the flocks as well as husbandry and managerial practices. A 1998 sheep farmers census carried out by CEIEPO's ESD was used as a guide so that an updated census could be elaborated. Non-registered farmers were identified and included through direct enquiry among the sheep farming community.

The updated farmer census obtained was transferred to a relational database manager (Microsoft© Access 2000) and each farmer was assigned a unique identifier code.

3.3.2 Case studies

In order to quantify some of the reproductive and productive parameters of Caojomulco's flocks, eight farmers were selected as case studies. The selection of these case studies was not random, but was chosen from farmers who were more acquainted with the work of the ESD and were willing to participate. Although such a selection criterion might produce biased results, it was chosen in order to collect data with a high degree of accuracy to provide reliable information, as suggested by Casley and Lury (1987). It is important to mention that sheep farmers in Coajomulco do not use any record-keeping system other than their own heads, therefore it was necessary to obtain the required information from scratch.

A system for record-keeping was set up for each of the eight flocks. Ewes and lambs were identified and the behaviour of both their reproductive and productive performance noted. Farms were visited fortnightly to update records and to monitor the occurrence and distribution of lambing as well as the pregnancy status of breeding ewes.

3.3.3 Participatory exercises

A participatory exercise using an aerial photograph was carried out with sheep farmers in order to identify grazing distribution patterns, location of crop plots and penning sites. This exercise was designed under the concept of "participatory GIS", which implies the involvement of communities in the production of GIS data and spatial decision-making (Abbot *et al.*, 1998; Jordan, 1999).

A high-resolution aerial photograph of the municipality of Huitzilac was obtained at the Mexican Geography and Statistics National Institute (INEGI). An A0 size print out of Coajomulco was shown to the sheep farming community. Farmers were asked to sketch on the enlarged aerial photograph the location of their flocks' penning sites as well as the extent of the grazing areas that were used by their flocks. Watering points, paths and access routes were also drawn. In addition, sheep farmers were invited to indicate the areas where their own flocks were habitually herded. Some information about preference and distribution in time and space of shepherding practices was also gathered.

The sketched data collected through this methodology were digitised using the software Cartalinx© 1.2 (Clark Labs) and subsequently transferred to a PC-based GIS, ArcGIS© 8.1 (ESRI) for storage and analysis. The farmers database described in section 3.3.1 was linked as the attributes associated with the spatial features.

3.3.4 Spatial definition of the area suitable for grazing

The information collected with the participatory exercises was also useful for the spatial identification of the expansion of the grazing zones. Although no formal methodology was followed, the use of aerial photography, knowledge of the area, and groundtruthing during fieldwork were applied. Compiling this information was necessary since the location of agricultural and urban areas, as well as the layout of water courses, roads and paths created a discontinuous grazing surface. The identification of the real grazing surface was important not only for a more accurate analysis of the variables of the grazing systems, but also to distinguish the access routes and the feasibility of travelling across the communal land when flocks graze.

As part of the GIS analysis of the grazing zones, a "buffer" routine was carried out to exclude from the grazing areas the expansion of what was considered as "non-suitable for grazing" area produced by line features. Thus, a buffer of 6 m was applied to tracks, 3 m for paths, 8 m for the railway line, 22 m for the motorway, and 10 m for other roads. Agricultural plots and the urban area were also excluded. Bridges or tunnels that flocks could use to cross over roads towards different grazing areas were also identified.

3.4 Results

3.4.1 Static survey

The sheep farming community of Coajomulco comprised thirty-eight farmers. Most farmers had a stock of breeding ewes with one or more rams, although there were four farmers that did not have breeding ewes and only acquired some lambs for rearing. Similarly, there were three farmers that did not own a ram and thus hired one during the reproductive season. Table 3-1 shows the number of breeding stock that each farmer owned. The average number of breeding stock was 32 sheep (s.e. = 4.4). Figure 3-4 summarizes these results in an histogram of the number of breeding stock per flock. The average ewe : ram ratio was 20, although this value ranged greatly from two to 72.

Table 3-1 Breeding stock by farmer in Coajomulco's sheep flocks

Farmer ID	Rams	Ewes	Farmer ID	Rams	Ewes
AC	1	72	JAM	1	0
AF	2	35	JE	1	11
AO	3	30	JHD	1	22
ARL	1	8	LAC	1	50
AVA	0	4	MAC	2	25
AZ	2	80	MH	1	25
BM	4	80	MM	2	18
CS	5	100	MV	3	45
DLU	3	30	ND	1	22
DOC	4	50	NE	1	15
EDC	5	44	PC	3	80
ERC	2	33	PEC	1	2
ESD	1	14	RF	0	4
EV	0	0	RTH	1	10
EZ	1	24	RUF	3	33
FC	1	51	RV	0	1
FD	1	21	SZ	1	20
HD	0	0	TOL	2	60
HJ	0	0	ZAE	2	30

The number of lambs that farmers reported having in the survey was related to the number of ewes per flock. The lamb : ewe ratio averaged 0.74, however it was not possible to estimate how much this figure was influenced by fertility and prolificacy parameters. The analysis of the survey also showed that the lambing season took place from October to March, peaking in December and January. This indicated that the reproductive season started in June and extended for approximately 26 weeks. Breeding seasonality in Coajomulco seemed not to be mainly affected by photoperiodicity but by the nutritional status of ewes, as reported for native sheep in Mexico (Galina *et al.*, 1996).

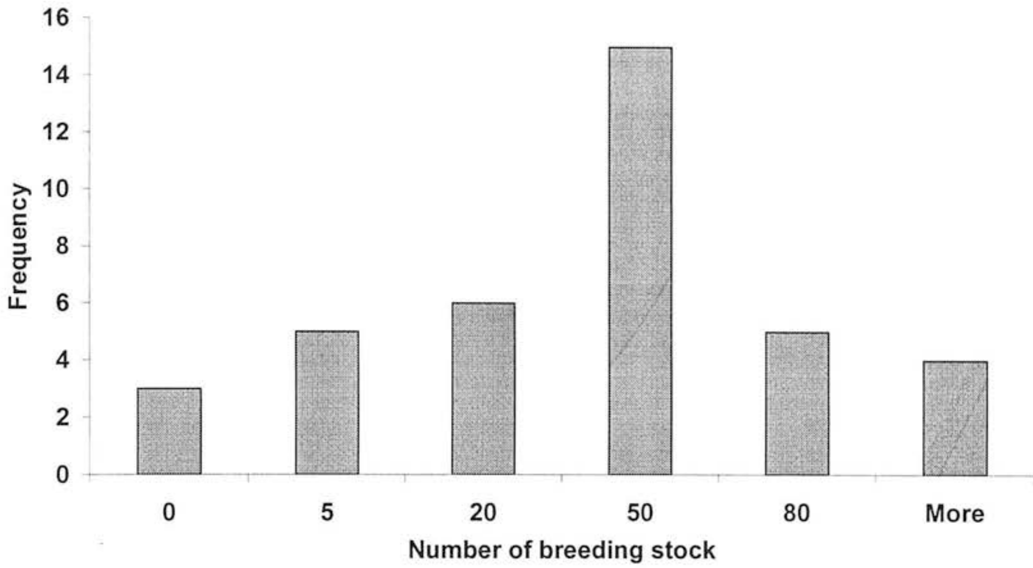

Figure 3-4 Histogram of breeding stock per flocks in Coajomulco

Feeding practices were totally determined by rain distribution and no use was made of external inputs. The rainy season ran from May to October and it was during these months that flocks made use of the plant material that grew across the communal land. The grazing season extended for two more months (November and December) due to the residual humidity kept in the ground. Every morning flocks were shepherded to forested and grassy areas of the region and brought back to their penning sites in the evening. The shepherd was usually the farmer or a close relative of his, although occasionally hired labour carried out this job. Regardless of their size, flocks were shepherded individually, and even very small flocks were looked after by one shepherd. The selection of the grazing zone where a shepherd would take his flock for a given day was made daily. Although this decision was mainly based on the proximity to the penning site, the shepherd often preferred to walk longer distances in search of "less crowded" grazing areas.

The agricultural calendar for the dry season meant the inclusion of harvest residues in sheep diets. Grazing was no longer practiced in the communal land for January, and animals were shepherded to maize and oats plots. After the maize grain was dry and harvested and oats had been used for hay, sheep grazed the dry plant residues that were left on the plots. Once this fodder source was over, sheep diet consisted of dry maize stover and occasionally oat hay until rain allowed the start of a new grazing season (mid May.

The survey results showed that the number of farmers that regularly offered salt or water when sheep were penned at night was only 35% and 45% respectively. The feeding regime was the same for all the animals in the flocks since they were not grouped according to their physiological status. According to the survey, only one farmer regularly provided supplement (commercial concentrate) for lactating ewes and lambs.

3.4.2 Case studies

From the eight flocks under surveillance, the reproductive performance of 70 breeding ewes was monitored. The averaged fertility rate per flock was 0.634 (s.e. = 0.048). Forty six ewes out of the original 70 gave birth and averaged a prolificacy rate per flock of 1.30 (s.e. = 0.067). The lambing season started in the first fortnight of October and the lambing distribution is shown in Figure 3-5.

Regarding the evaluation of weight gain in lambs, the weight of 28 lambs was monitored over eight months. Figure 3-6 shows the growth curve for these lambs. The averaged daily weight gains from birth to two, two to four, and four to eight months of age were, 136 g (s.e. = 5.42), 53 g (s.e. = 6.58) and 58 g (s.e. = 3.79) respectively.

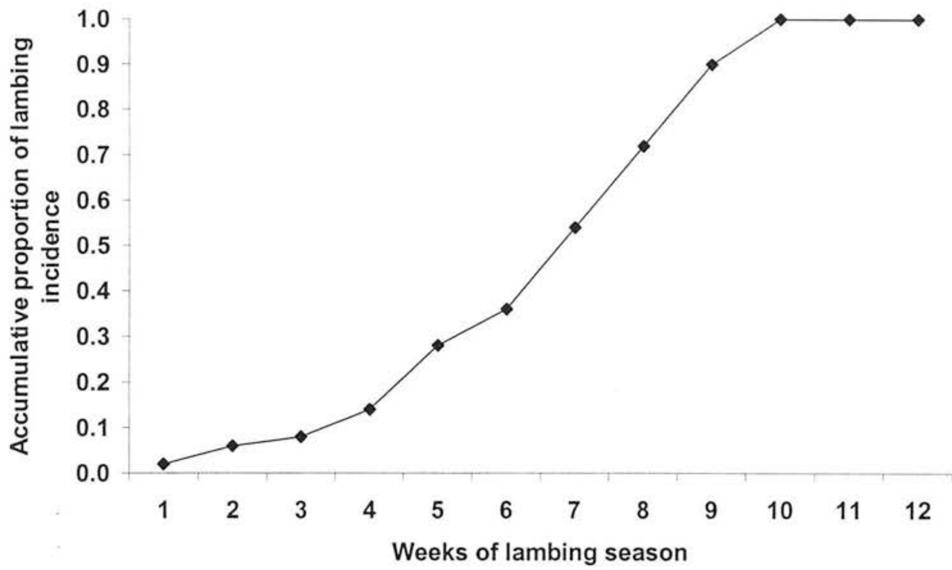

Figure 3-5 Lambing distribution during lambing season shown as accumulative frequency. Beginning of lambing season = first fortnight of October

The reproductive performance indicators obtained for the case studies were consistent with those reported for flocks in Fierro del Toro (another parish within the municipality of Huitzilac) by Bravo (1993). Reports of daily weight gain for lambs reared under native forage grazing systems in the temperate zone of Mexico are scarce. However, Hernández-Mendo *et al.* (2000) reported an average daily weight gain of 85.3 g for growing lambs in the highlands of central Mexico with *Pennisetum clandestinum* pastures. Some results for hair breeds have indicated a range of 40 g up to 160 g for suckling lambs (Aguirre *et al.*, 1990; Castillo *et al.*, 1974; Pedraza and Perezgrovas-Garza, 1991; Pedraza *et al.*, 1997), and 21 g to 43 g for weaned lambs (Pedraza and Perezgrovas-Garza; 1991) in grazing systems of the Mexican tropics .

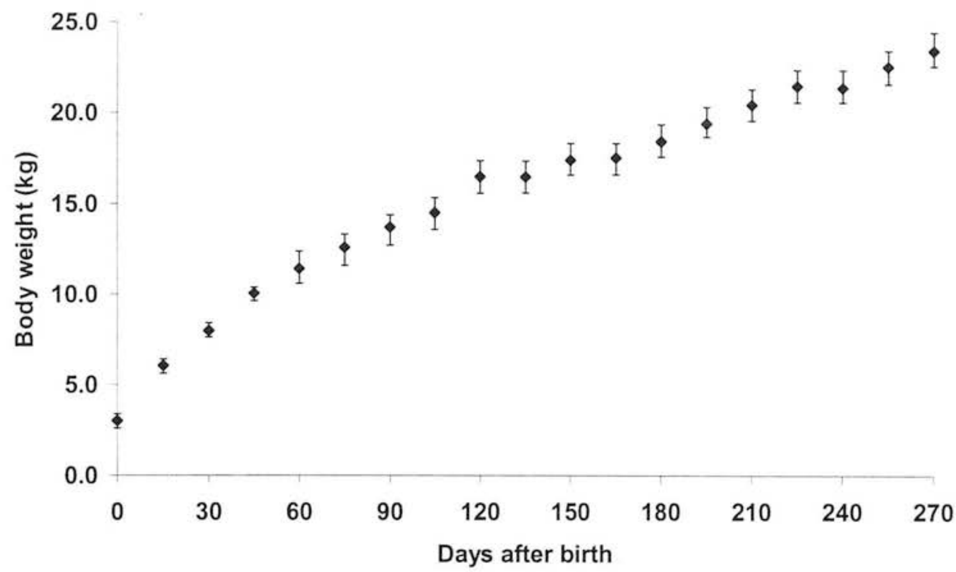

Figure 3-6 Growth curve for lambs in Coajomulco, from birth until nine months of age

3.4.3 Participatory exercises

Figure 3-7 shows the location of the 38 penning sites during the grazing season. The information sketched on the aerial photograph revealed that there were 11 different grazing zones distinguishably isolated from each other. The grazing zones were distributed around the parish's urban centre and were primarily defined by the layout of roads, water courses and the main path that ran in the middle of the town from south to north. Secondly, agricultural land location, the railway line and terrain features influenced the distribution of the grazing areas. Figure 3-8 shows their location and area. The areas were numbered clockwise starting from the one located immediately contiguous to the parish town at the south.

The selection of the grazing areas was also found to be influenced by both the proximity to night enclosure sites and one watering point situated in the grazing zone 7 (northeast). The participatory exercise also revealed that during the grazing season 65% of the flocks did not change their grazing area, 20% changed once, and 15% did so twice.

3.4.4 Spatial identification of area suitable for grazing

Figure 3-9 shows the layout of the corrected grazing area after applying the "buffer" procedure and removing the grazing exclusion area and the agricultural land. Bridges and tunnels that could be used by sheep flocks are also marked in Figure 3-9. The location of these access points are important to cross over the motorway and the road. It can also be appreciated that the intermittent water courses throughout the landscape have created dry channels or ditches that are an obstacle for the free movement of flocks. Continuous flock transit have created crossing points in those dry channels, which were also marked in the map of Figure 3-9.

3.5 Conclusions

This chapter has presented the methodology and results related to the characterisation of the events that took place within the farming systems of Coajomulco and that influenced the utilisation of forage by sheep flocks. The quantification of these events emphasizes the analysis of the grazing system as a dynamic process influenced by environmental and management elements. Despite the fact that Coajomulco's communal grazing system seems to be highly influenced by environmental factors, flock management decisions might have even greater influence in the final performance of the systems as suggested by Pollot (1987).

Since feed intake is fundamental in the study of grazing systems (Finalyson *et al.*, 1995), quantifying the parameters that define flock dynamics allows the temporal pattern of forage demand to be obtained. In addition, the inclusion of geographically referenced data provides a spatial framework for the regional analysis of the grazing system. All this information will be assembled in a grazing optimisation model in Chapter 7.

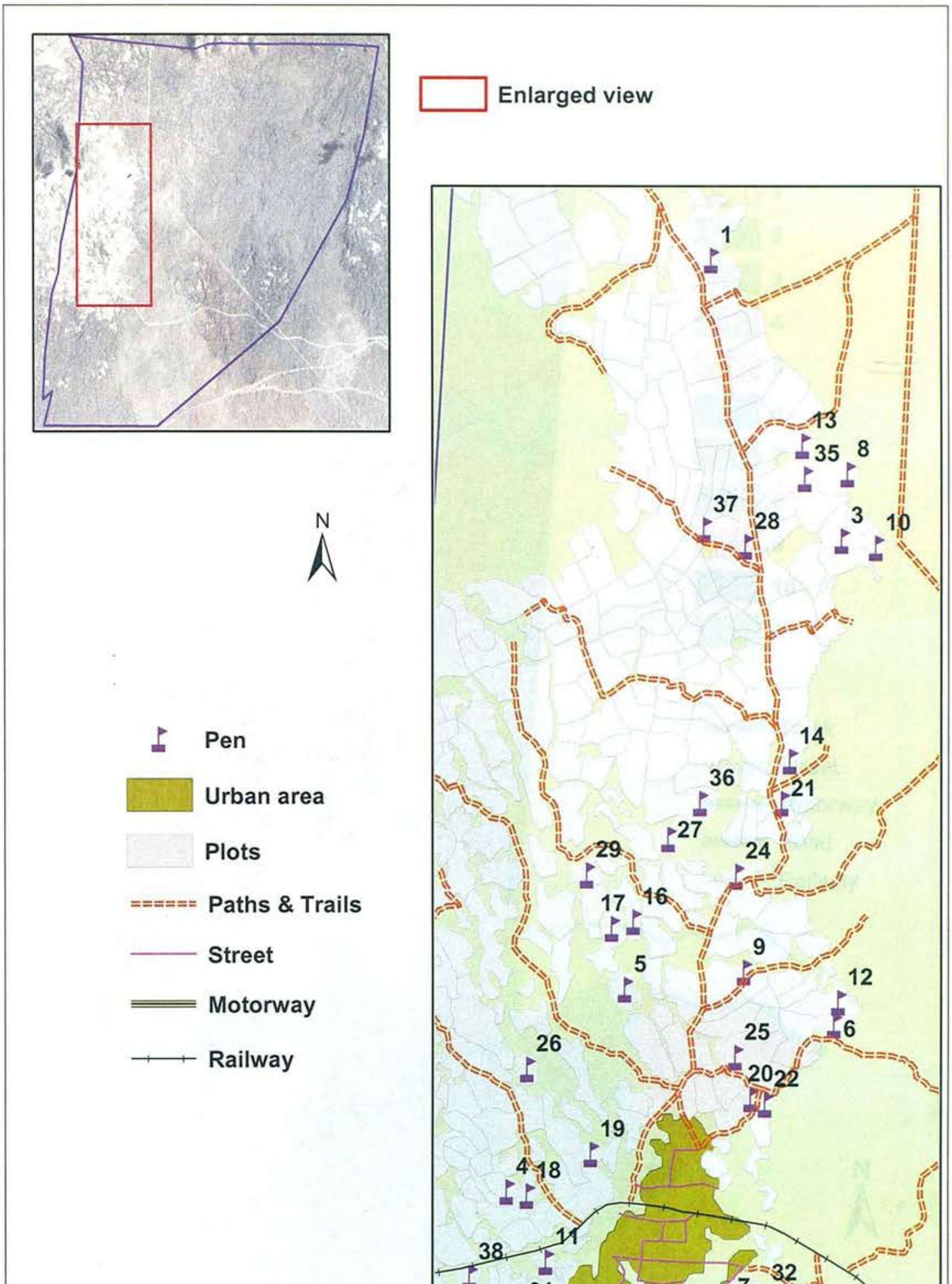

Figure 3-7 Location of penning sites in the agricultural area for each of the 38 sheep flocks of Coajomulco

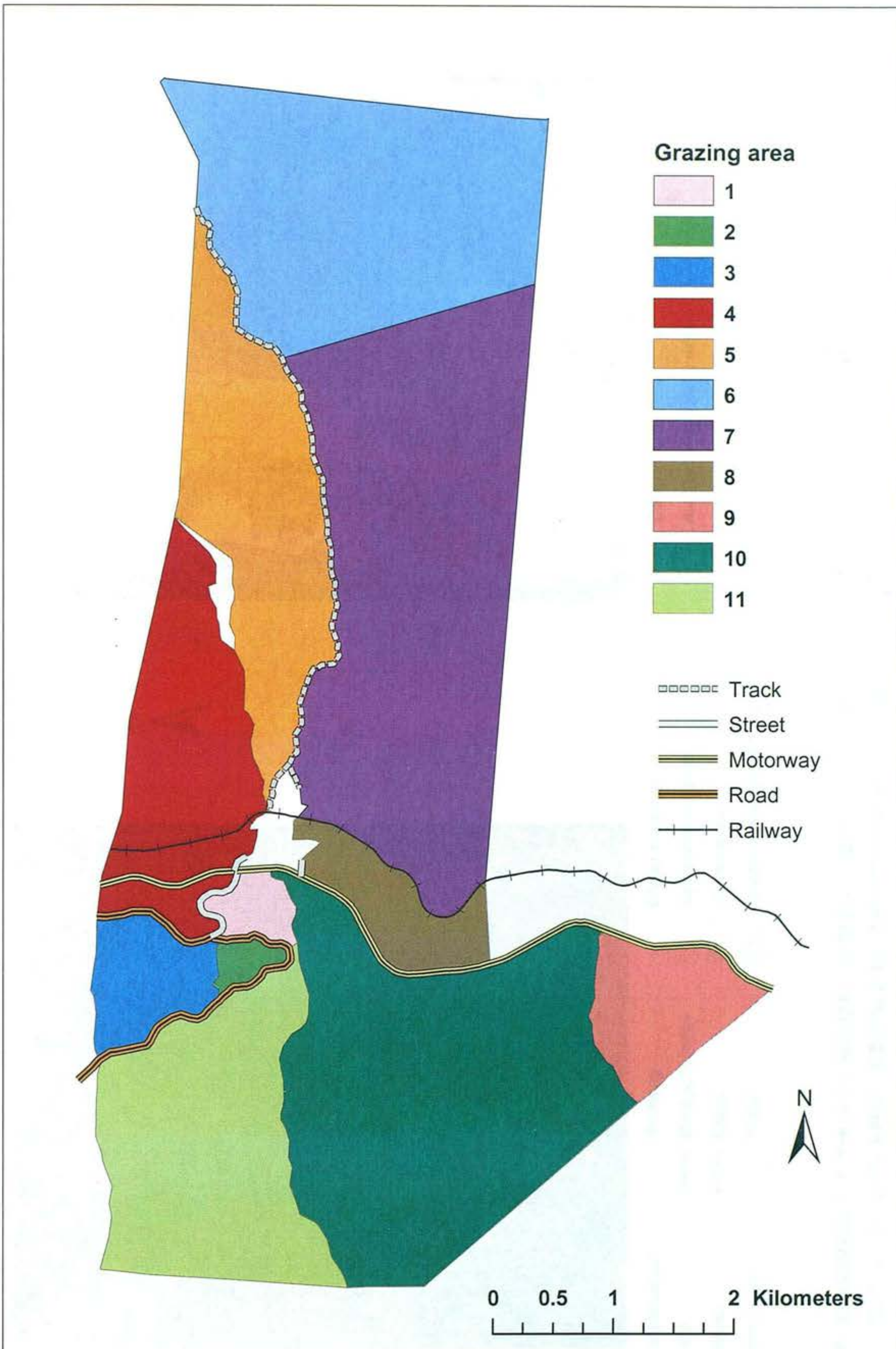

Figure 3-8 Location of grazing areas across Coajomulco as identified through the participatory exercise

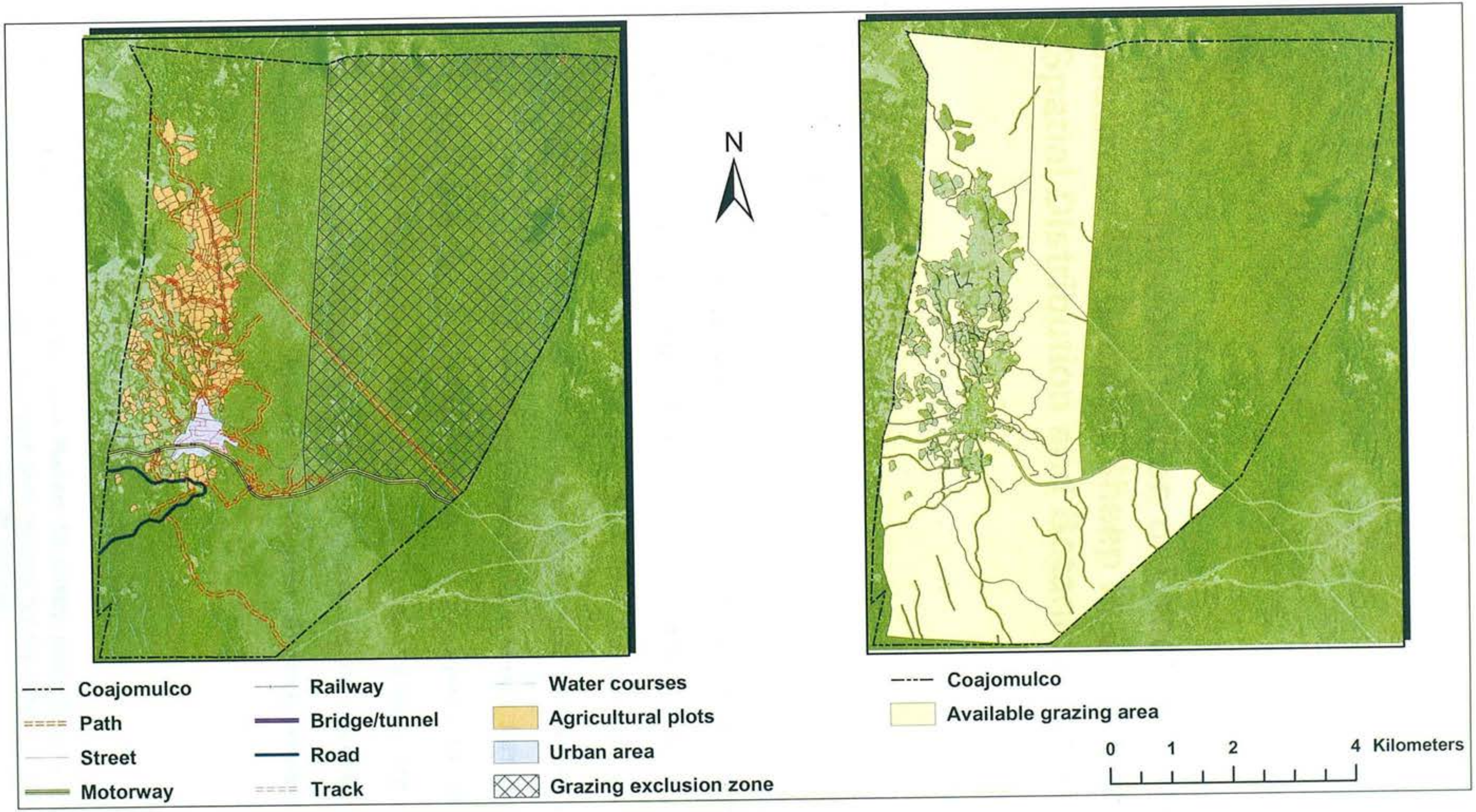

Figure 3-9 Identification of the area suitable for grazing after correction using a "buffer" procedure on the layout of line features and removing the exclusion grazing area, the parish town and agricultural plots

Chapter 4

Regional Characterisation of Local Grazing Resources for Grazing Sheep in Coajomulco. I. Spatial Distribution and Botanical Analysis

4.1 Introduction

In the previous chapter, consideration was given to the animal element of the grazing system of Coajomulco. Now, an analysis of the plant element of the system will be presented. Unfortunately, the fundamentals of grazing ecology have not yet been extensively studied in temperate regions of developing countries for traditional smallholder sheep farming systems. Thus, there is a gap of information relating to aspects of productivity, defoliation and trampling resistance, nutritional content, anti-nutritional factors and vegetation dynamics, etc. Differences in environmental and managerial regimes have limited information sharing between scientific

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Some of the contents of this chapter have been included in:

González-Estrada E., Fawcett R.H. and Herrero M. (2002): Integrating models of relative abundance of species with the dry-weight rank method for the botanical analysis of forest understorey vegetation. *Grass and Forage Science*, **57**, 171-183.

groups or the creation of databases about native forage species. In addition, smallholder systems mainly rely on traditional and/or expert knowledge that frequently has not been efficiently disseminated (see Chapter 2).

During the preliminary stage of this work, it was evident that a big gap existed in the availability of information on traditional grazing systems in central Mexican forests. Even at the most basic level, information on grazed species was lacking, thus precluding the existence of productivity and nutritional profiles of the relevant plant species. The study presented here contributes to filling this information gap, being one of the first studies to document basic information of native grazing resources for the highlands of Mexico. The information will be presented in five points: i) spatial distribution of plant communities, ii) botanical composition, iii) productivity and regrowth capacity, iv) identification of edible species, and v) nutritional value.

Due to the amount of information and ease of readability, the analysis of grazing resources will be presented in two chapters. This chapter contains information that can be described as relating to the variability of the grazing resources in a spatial context, since it deals with the botanical composition and its spatial arrangement. Chapter 5 focuses on the characteristics that are inherent in the morpho-physiological of the plant, e.g. productivity and nutritional composition.

This chapter is divided in three main sections. Section 4.2 focuses on the spatial distribution of the plant communities at a regional scale with the use of remote sensing techniques. Section 4.3 presents the implementation of the sampling methodology for botanical composition applied in this study.

Finally, section 4.4 reports the findings for the botanical composition of Coajomulco's plant communities.

4.2 Mapping of vegetation cover in Coajomulco by remote sensing techniques

As mentioned in Chapter 3, the conservation value of the "Corredor Biológico Chichinautzin" partly lies in the biodiversity of local plant communities (SEDUE, 1989; SARH, 1992). Such biodiversity is to some extent attributed to a range in altitude of the study area of 1 000 m, which produces a complex arrangement of plant communities. Thus, Coajomulco's local grazing resources are included within very heterogeneous and diverse plant communities. The first step to undertake for the analysis of grazing resources was to design an appropriate methodology to identify the regional vegetation and land cover.

Remote sensing techniques have been widely recognised as accurate and cost-effective tools for producing regional vegetation and land cover (e.g. Kremer and Running, 1993; Davis *et al.*, 1994; Walsh and Davis, 1994). The analysis of vegetation cover through satellite images has been reported as being of great utility in the analysis of extensive grazing systems in addressing issues of spatial variability of grazing resources (Loseen *et al.*, 1995; Hill *et al.*, 1996). It was therefore decided that this would be a suitable approach for this study.

A relatively simple and direct remote-sensing approach was undertaken to determine the land cover of Coajomulco in order to estimate the spatial variability of grazing resources. For the study of Coajomulco's grazing resources, it was assumed that there was a direct link between the forest's tree canopy (remotely sensed data) and the understorey vegetation (niche with potential for grazing). The association between understorey vegetation composition and canopy structure has in fact been suggested by Beatty (1984), Kamara *et al.* (1998) and Bandara *et al.* (1999); and a previous study in the area by Hernández (1977) described the presence of such an association.

4.2.1 Methodology

A six-band Landsat 7 ETM+ (Enhanced Thematic Mapper plus) image acquired on April 20, 1999 served as the main source of remotely-sensed data. The image covered all the area of Coajomulco with a spatial resolution of 30 m × 30 m. This image was kindly donated by the Institute of Geography, National Autonomous University of Mexico. The ETM+ data were geometrically corrected to the projected coordinate system NAD 1927, UTM zone 14. Image processing functions required for the analysis and classification methodology were performed using Idrisi© 32.22 (Clark Labs).

A maximum-likelihood algorithm (Eastman, 2001b) for a supervised classification procedure was used on a three-band (green, red and infrared) false colour composite image (see Figure 4-1). A supervised classification procedure requires that examples of cover classes ("training" sites), extracted from an image, are previously identified in order to produce a statistical characterisation of the reflectance produced by the pixels of each class (Bourne and Graves, 2001; Eastman, 2001a). Thus, "training" data to assist the classification procedure, were obtained from a 1 : 50 000-scale land use map of the area (CETENAL, 1976). This map described the land cover of Coajomulco in four different classes: i) urban, ii) agricultural, iii) scrub and grassland, and iv) woodland. The woodland class was further divided into seven different categories according to the type of wood (coniferous, deciduous or mixed) and the relative proportion of the dominant tree species in each of them. These woodland types were labelled arbitrarily using the capital letters A to G. Table 4-1 shows describes the different types of woodland that were included in the analysis.

Thus, "training" sites for each of the ten land and vegetation cover classes were defined and then verified empirically by the author's own knowledge of the study area and field survey data from October and November, 1999. The field survey was carried out with the assistance of a Global Positioning System (GPS) receiver and a set of 1994 aerial photographs scale 1 : 40 000 produced by the INEGI.

Table 4-1 Description of the different types of woodland class in Coajomulco according to CETENAL (1976)

Class	Woodland type*	Predominant tree species
Woodland A	C	*Abies religiosa*
Woodland B	C/D	*Pinus teocote*, *Pinus leiophyllus*, *Alnus jorullensis*
Woodland C	C/D	*Pinus teocote*, *Quercus rugosa*, *Alnus jorullensis*
Woodland D	D	*Quercus obtusa*, *Quercus rugosa*, *Arbutus glandulosa*
Woodland E	C/D	*Pinus leiophylla*, *Alnus jorullensis*, *Pinus teocote*
Woodland F	C	*Pinus montezumae*, *Pinus leiophylla*, *Abies religiosa*
Woodland G	C	*Abies religiosa*, *Pinus montezumae*

* C= coniferous, D = deciduous

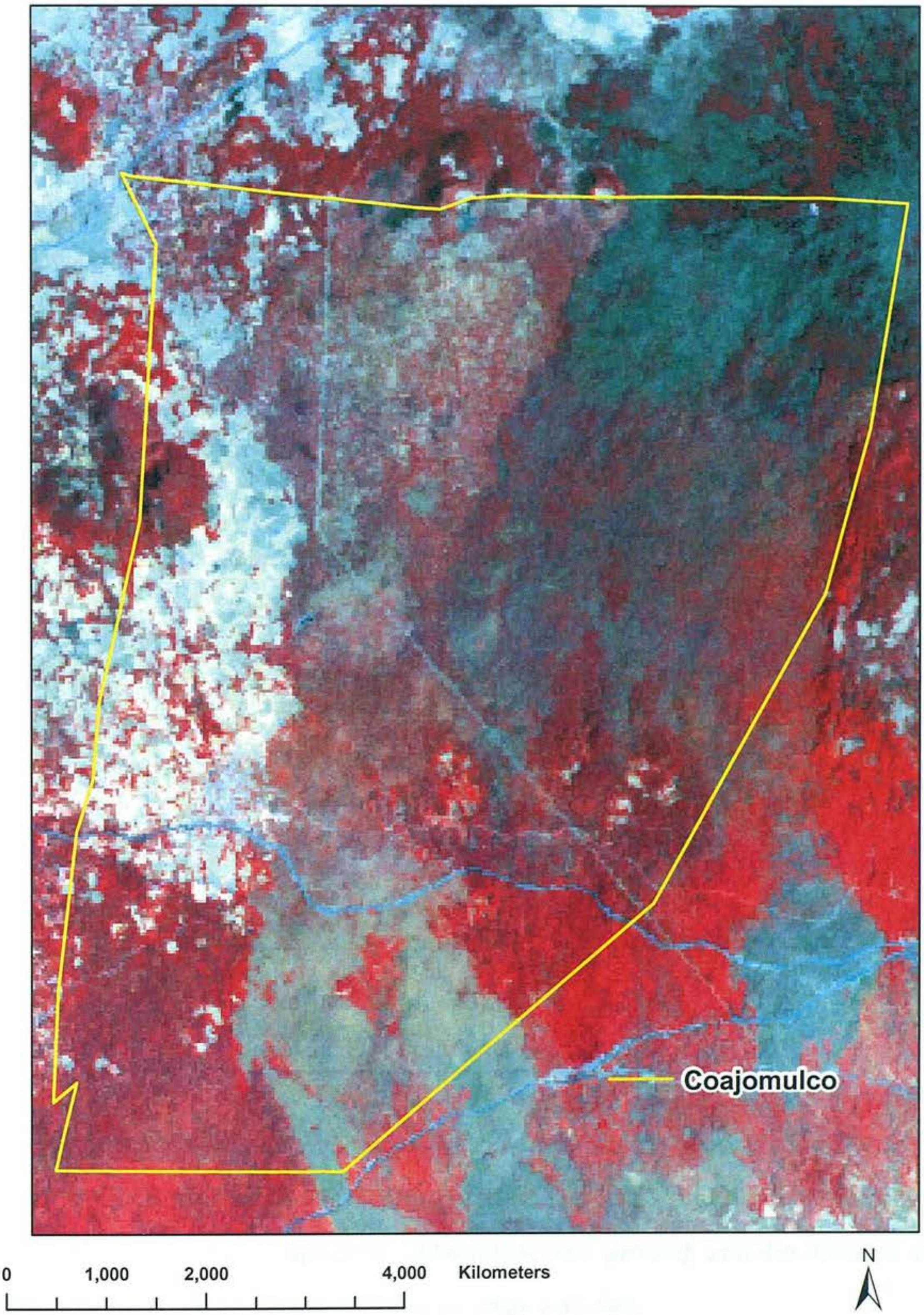


Figure 4-1 Landsat thematic mapper plus (ETM+) false colour composite image of the study area

4.2.2 Image classification procedure results

For display and further analysis purposes, the classified data were corrected using a modal 5 × 5 filter and were subsequently "polygonized". Finally, polygons were smoothed with a low pass generalisation filter. Figure 4-2 shows the resulting land cover classification image for Coajomulco. Table 4-2 indicates the cover percentage of each land and vegetation class.

Table 4-2 Extension of land and vegetation classes produced by the supervised classification of Coajomulco's remotely sensed data

Class	Area (ha)	Area (%)
Urban	30.7	0.5
Agricultural	546.0	8.9
Scrub & grass	1 006.1	16.4
Woodland A	509.2	8.3
Woodland B	1 963.2	32.0
Woodland C	791.4	12.9
Woodland D	527.6	8.6
Woodland E	257.7	4.2
Woodland F	392.6	6.4
Woodland G	104.3	1.7

The fact that the image was taken at the end of the dry season gave rise to a well defined mosaic of vegetation patches. The grass and scrub vegetation had died back, most of agricultural land was bare ground, and the distinction between the coniferous and deciduous trees was clear.

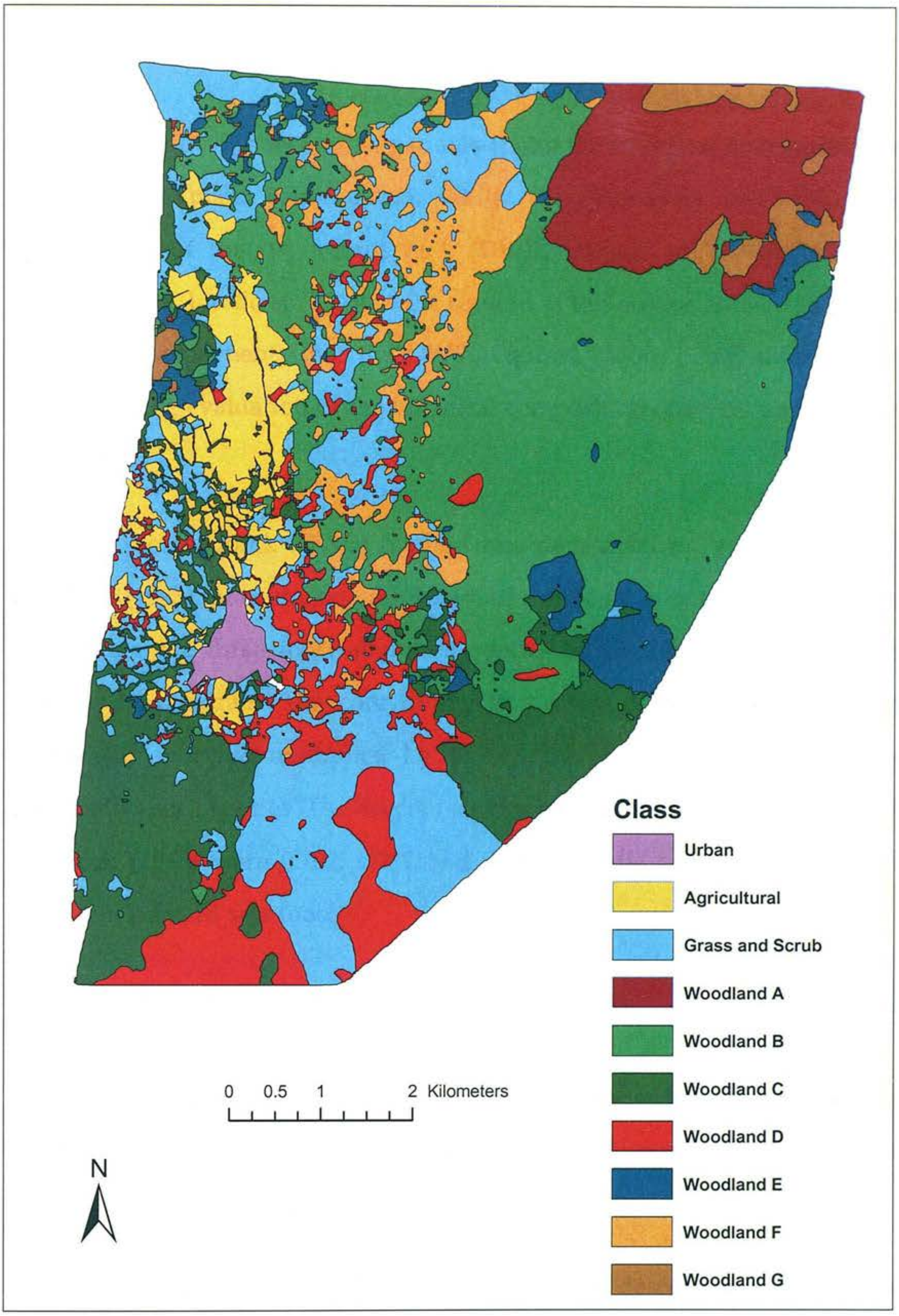


Figure 4-2 Land and vegetation cover map of Coajomulco as produced by the supervised classification procedure of the satellite image

4.3 Analysis of the botanical composition of the plant communities in the communal grazing areas of Coajomulco

The objective of this section was to determine the botanical composition of Coajomulco's plant communities, whilst simultaneously evaluating the applicability of the dry-weight rank (DWR) method of 't Mannetje and Haydock (1963) to do so. Most of the content of this section is focused on the theoretical adjustments that the DWR required before being satisfactorily applied to the evaluation of the botanical composition of forest understorey vegetation.

The Dry-Weight Rank (DWR) method was developed by 't Mannetje and Haydock (1963) for estimating the botanical composition of grassland swards by ranking the three most abundant species by dry weight in each of a number of quadrats. The core of the methodology consists of a set of coefficients that are multiplied by the relative frequencies of the ranks assigned to each species. The original coefficients derived by 't Mannetje and Haydock (1963) were 0.702, 0.211 and 0.087 and the contribution of each species in a sward was thus:

$$DW_i\% = 0.702 \times X_{1i} + 0.211 \times X_{2i} + 0.087 \times X_{3i} \qquad (4\text{-}1)$$

where, $DW_i\%$ is the estimated dry-weight percentage of the *i*-th species, and X_{1i}, X_{2i} and X_{3i} are the relative frequencies of the first, second and third ranks respectively of the *i*-th species.

The practicalities of the DWR method as a non-destructive method for producing reliable botanical analysis in grassland swards have motivated the development of further research either to improve its applicability, use and accuracy or to drive discussion of the theoretical assumptions behind the derivation of its coefficients (e.g. Tothill, 1978; Jones and Hargreaves, 1979; Sandland *et al.*, 1982; Scott, 1986; Neuteboom *et al.*, 1998; Nijland, 2000).

Although originally developed for tropical grasslands, the DWR method has been used extensively under different climatic conditions and a broad range of vegetation types. The method has been used widely in agricultural research (e.g. Bryan and Evans, 1973; Mclean *et al.*, 1981; MacLeod *et al.*, 1993; dos Santos *et al.*, 1998; Ibrahim and 't Mannetje, 1998) and there is evidence of its use in ecological and wildlife research (Evans and Jarman, 1999; Woolnough and Johnson, 2000). In addition, the method has been used with forb and grass species in prairie vegetation (Parajulee *et al.*, 1997), as well as in the herbaceous strata of mountainous vegetation (Martinez, 2000).

The DWR method has varied very little from 't Mannetje and Haydock's (1963) original proposal, and its use has been restricted to plant communities with a relatively small number of species. Walker (1970) reported the failure of the method to predict satisfactorily the botanical analysis of a "very heterogeneous" South African thornveld. Walker concluded that the number of species ranked during the field sampling was less than the actual number of species present in the sward. The main problem appeared to be that the DWR method neglected the presence of minor species which, unless ranked collectively either as a single unit or few groups, could have created a considerable divergence in the final botanical analysis.

In highly diverse plant communities with a rich assemblage of species, the dominance exerted by the most abundant species over the rest of the community is very low, and therefore the abundance of species is more evenly distributed. The principal shortcoming of the DWR method is that scoring three ranks cannot satisfactorily explain the distribution of species in plant communities where the dominance level of the most abundant species is lower than in typical grassland swards. The variant of the DWR method described by Nijland (2000) utilizes coefficient values proportional to the abundance percentages of the three most abundant species. Although this approach improves the accuracy of the DWR method in predicting the botanical composition of grassland swards, it is considered that it would neglect the least abundant species in plant communities where the dominance of the most abundant species is low.

Applicability of the DWR method in forest understorey vegetation

The studies of 't Mannetje and Haydock (1963) and Jones and Hargreaves (1979) established empirical abundance distributions of species in grassland swards from which the DWR method coefficients were derived. Sandland *et al.* (1982) pointed out that these empirical distributions satisfactorily represented the "relatively narrow range of probabilistic mechanisms" that determine the abundance of species in such grassland swards. However, the probabilistic functions that describe the abundance distribution of species in grassland swards may not be the same as those of highly diverse plant communities (Crawley, 1997). For these plant communities, the DWR method will have to rank a higher number of species and to assign a correspondent coefficient for each extra ranked position created. Thus, to use the DWR method to rank more than three species simultaneously, firstly the theoretical probabilistic function that explains the relative abundance distribution (RAD) of species within the plant community under study must be found. This probabilistic function can subsequently be used, according to the number of recorded ranks, to derive the number and values of the coefficients required. The derived coefficients for the DWR method will therefore reflect the same assemblage of species that define the RAD of the species of a given plant community.

Several mathematical models that explain the relative abundance distribution of species in plant communities have been produced. Useful reviews of the most common RAD models have been made by May (1975), Pielou (1975), Magurran (1988) and Tokeshi (1993). Some RAD models have been classified as niche-apportionment models (Tokeshi, 1990), and are useful for analysing ranked-abundance data (Pielou, 1975; Wilson, 1991). The fit of the DWR coefficients has already been tested with some of these RAD models, such as the Geometric model (Scott, 1986) and Poisson-distributed models (Sandland *et al.*, 1982; Neuteboom *et al.*, 1998).

The objective of this section was therefore to extrapolate the applicability of the DWR method to plant communities that differ from typical grassland swards in that they comprise a high diversity of species. To do so, firstly four different RAD models were considered in order to produce the DWR method coefficients. The effect of modifying the number of ranks scored by the DWR method was subsequently evaluated.

4.3.1 Data collection

The sampling was carried out over a period of three months, June to August 2000, during the rainy season. The botanical composition of the understorey vegetation of each of the seven woodland classes reported in section 4.2.2 was sampled. The sampling was carried out up to an aboveground vegetation height of 1.20 m, the grazing horizon of the sheep in the area. As the objective of this methodology was related to grazing processes and carrying capacity estimators, the sampling was focused on grasses, herbaceous species, ferns and shrub plants.

The sampling strategy was designed with the aid of a GIS and comprised a sampling area of 3313 ha within the parish of Coajomulco. All the vegetation classes defined in section 4.2.2 were included within it. Following a north-south direction, parallel transects were drawn across the sampling area. The first transect was made 250 m from the western boundary of the sampling area and then the following transects were spaced at 500-m intervals parallel to the first. This thus gave a total of ten transects, ranging between 2197 m and 8258 m in length, with an average length of 7042 m. With the help of a GPS receiver, transects were walked during sampling and field measurements were pinpointed within the corresponding vegetation class.

4.3.2 DWR method technique

The DWR method was carried out with a $1m^2$ quadrat placed at 250-m intervals along the transects. Four rods were placed at each corner of the quadrat and a string positioned at a height of 1.20 m to set a sampling unit of 1 m × 1 m × 1.20 m. The observer ranked and recorded all the species present as described by 't Mannetje and Haydock (1963). In contrast to the original method, the number of ranks scored was equivalent to the maximum number of species found in a single quadrat; thus from eight to twelve species were ranked depending on the woodland class. The collected data were tabulated to obtain the relative frequencies of the ranks of each species to be multiplied by the respective coefficients. The derivation of these coefficients will be described in section 4.3.5.

Firstly, botanical compositions were produced by the DWR method using the maximum number of ranks assigned in each vegetation class. Unless otherwise explained, the DWR method used was that modified for the higher number of ranks. Botanical compositions with the DWR method were thus obtained:

$$DW_i\% = \sum_{q=1}^{Q} m_q \times X_{qi} \qquad (4\text{-}2)$$

where, $DW_i\%$ was the estimated dry-weight percentage of the *i*-th species, Q was the total number of ranks recorded, m_q was the coefficient associated to the rank, and X_{qi} was the relative frequency of the *q*-th rank of the *i*-th species. An outline of the methodology used to apply the DWR method to the understorey vegetation of this study is summarised in five stages as follows:

(vi) The botanical composition of the understorey vegetation of each woodland class was obtained with the point-quadrat (PQ) method.

(vii) Different RAD models were tested to fit the botanical composition of each class.

(viii) The RAD model with the best fit was subsequently used to produce the coefficients (m_q) that multiply the relative frequencies of each species (X_{qi}) in the DWR method. The botanical composition of the understorey vegetation of each class was obtained with the DWR method.

(ix) The reliability of the DWR method with the maximum Q value was tested by comparing it both with the botanical composition produced by the PQ method and with the RAD model.

(x) For each vegetation class, a set of different botanical compositions was produced, gradually reducing the number of ranks scored (Q). Quality of botanical compositions within sets was compared with the RAD model.

4.3.3 Point-quadrat method

The PQ method was undertaken as described by Goodall (1952). A thin rod was placed at 100-m intervals along the transects and all the leaves and young stems of species located below 1.20 m that touched the rod were recorded. The data collected were interpreted as percentage cover. Botanical compositions for each of the seven woodland classes were obtained with this method and were subsequently used to fit the RAD models.

4.3.4 Selection of the RAD model

Four different RAD models from the literature (Table 4-3) were tested for their ability to explain the botanical composition produced by the PQ method. All of these models have been classified as niche-apportionment models (Tokeshi, 1990) since they describe the distribution of species abundance in a community according to a particular way of partitioning a common and limiting resource or niche among species. The models are based on the assumption that the fraction of the niche space apportioned to a species is proportional to its abundance (May, 1975; Pielou, 1975; Sugihara, 1980).

Table 4-3 Description of the models under analysis

Model	Source	Niche selection process	Condition
Geometric	Motomura (1932)	Deterministic	$x_i = m(1 - m)^{i-1}$
Random-fraction	Tokeshi (1990)	$0 \leq p_i \leq 1$	p_i = uniform random number
Broken-stick	MacArthur (1960), Tokeshi (1993)	$p_i = \alpha x_i$	$\sum \alpha x_i = 1$
Power-fraction	Tokeshi (1996)	$p_i = \alpha x_i^k$	$\sum \alpha x_i^k = 1$

x_i = niche segment size (relative abundance) of the *i*-th species, m = parameter of the model, p_i = probability of *i*-th segment to be selected for division, α = constant, k = parameter of the model.

The Geometric model (Motomura, 1932) is a deterministic model, which suggests that the most abundant species takes an m proportion of the total niche, the second most abundant takes the same proportion, m, of the remaining niche, and so on. The other three models are stochastic and a random number with a uniform distribution determines their niche apportionment rule. In the Random-fraction model (Tokeshi, 1990), the niche fraction to be split is chosen randomly regardless of its size. In the Broken-stick model (MacArthur, 1960; Tokeshi, 1993), the probability that a fraction will be chosen is a linear function of the fraction size. Finally, in the Power-fraction model (Tokeshi, 1996), the probability that a niche fraction is selected for division is proportional to the sizes of existing fragments raised to the exponential parameter, k.

The Geometric model was evaluated with different values of m, ranging from 0.05 to 0.95, with a step of 0.05. For each of the stochastic models, 10000 simulation runs were performed using the niche division algorithms developed by Drozd and Novotny (2000). Goodness-of-fit of the stochastic models was assessed using the averaged values of these multiple runs. The k

value for the Power-fraction model was tested using the same range employed for the parameter m in the Geometric model.

Goodness-of-fit of models was evaluated according to the following criteria: i) adjusted coefficient of multiple determination (R^2_{adj}), ii) first-order positive autocorrelation among residuals assessed by the Durbin-Watson test statistic (d), iii) residual standard deviation (RSD) and iv) goodness-of-fit for the cumulative probability function assessed by the Kolmogorov-Smirnov test statistic (D).

4.3.5 Integrating the RAD model with the DWR method

Once the best fitting model and its parameters were determined, the RAD models that were selected for each class were run again, setting the number of species equal to the number of coefficients needed (maximum Q value) by the DWR method. The derived coefficients (m_q) were scaled to sum one and multiplied by the relative frequencies of the ranks assigned to each species in the same way as in the original DWR method of 't Mannetje and Haydock (1963). A botanical composition for each of the seven woodland classes was thus produced.

4.3.6 Testing the DWR method

The botanical composition values obtained with the DWR method were compared with both the theoretical RAD model from which the coefficients were derived, and the botanical composition obtained with the PQ method.

Firstly, reproducibility of the modelled RAD of species by the DWR method was assessed with the concordance correlation coefficient (ρ_c) developed by Lin (1989). Secondly, concordance in the ranking of species between the DWR method and the PQ method was evaluated with Spearman's rank-order correlation coefficient (r_s). In order to compare goodness-of-fit between vegetation classes, regression analyses for the DWR method results against the modelled RAD were also performed. Further analyses were carried out to determine any relationship between goodness-of-fit indicators and biomass and diversity values.

4.3.7 Assessment of number of ranks scored

Further analysis was carried out to evaluate the effect of reducing the number of ranks scored in each vegetation class. A set of different botanical compositions was produced with the DWR method as described by Equation (4-2), with values for Q progressively reduced by one from the maximum Q value in each vegetation class to Q = 3. Coefficient values (m_q) were recalculated using the best fitting RAD model adjusted to the new values of Q. The goodness-of-fit within each set for the botanical compositions against the modelled RAD was evaluated by comparing both RSD and the number of species registered.

4.3.8 Results and discussion

Results for the number of species detected by the PQ method are shown in Table 4-4. It is also indicates the maximum number of ranked species per quadrat (maximum Q value) when performing the DWR method. The number of ranks assigned was dependent on the maximum number of species found in a single quadrat across each vegetation class.

Table 4-4 Number of species and maximum number of ranks scored (Q) by vegetation class

Vegetation class	Number of species	Maximum number of ranks scored
Woodland A	27	9
Woodland B	52	12
Woodland C	90	11
Woodland D	80	12
Woodland E	50	9
Woodland F	38	12
Woodland G	42	10

Comparison of models

The goodness-of-fit statistics for the PQ data and the models considered are shown in Table 4-5. The Geometric and the Power-fraction models indicated in Table 4 are those with the best fitting m and k values respectively, tested within a range of 0.05 to 0.95.

The greatest R^2_{adj} values were found for the Power-fraction model, except for classes A and E where the Geometric model had higher values. In the rest of the classes, both the Geometric and the Broken-stick model showed very similar R^2_{adj} values. For all the classes, the Random-fraction model obtained the lowest R^2_{adj} values.

Table 4-5 Comparison of models according to adjusted coefficient of multiple determination (R^2_{adj}), Durbin-Watson test statistic (d), residual standard deviation (RSD), and Kolmogorov-Smirnov test statistic (D).

Class	Model type	R^2_{adj}	Durbin-Watson d	Durbin-Watson Autocorrelation[†]	RSD[‡]	Kolmogorov-Smirnov D	Kolmogorov-Smirnov Significance
A	GM (m = 0.81)	0.99	1.87	No	35.8	1.23	NS
	RF	0.85	0.57	Yes	127.3	1.63	**
	BS	0.96	0.46	Yes	63.2	0.95	NS
	PF (k = 0.50)	0.98	1.12	Inconclusive	47.7	0.68	NS
B	GM (m = 0.87)	0.96	0.90	Yes	31.7	2.26	**
	RF	0.81	0.22	Yes	72.8	2.84	**
	BS	0.97	0.47	Yes	28.3	0.69	NS
	PF (k = 0.61)	0.99	1.43	No	11.6	1.08	NS
C	GM (m = 0.90)	0.93	1.07	Yes	17.3	3.52	**
	RF	0.80	0.11	Yes	30.3	4.08	**
	BS	0.94	0.71	Yes	16.0	1.20	NS
	PF (k = 0.58)	0.98	1.50	No	8.8	1.28	NS
D	GM (m = 0.89)	0.93	1.01	Yes	59.0	3.16	**
	RF	0.84	0.11	Yes	88.2	3.40	**
	BS	0.92	0.72	Yes	60.8	1.03	NS
	PF (k = 0.44)	0.99	1.71	No	24.9	1.27	NS
E	GM (m = 0.81)	0.96	0.71	Yes	53.7	2.80	**
	RF	0.83	0.80	Yes	114.4	2.50	**
	BS	0.90	0.36	Yes	87.3	0.90	NS
	PF (k = 0.35)	0.95	1.33	Inconclusive	60.1	1.00	NS
F	GM (m = 0.87)	0.97	0.60	Yes	79.1	0.80	NS
	RF	0.77	0.44	Yes	211.6	1.72	**
	BS	0.98	0.87	Yes	62.1	0.80	NS
	PF (k = 0.73)	0.98	1.30	Inconclusive	56.4	0.57	NS
G	GM (m = 0.81)	0.93	1.29	Inconclusive	59.3	2.51	**
	RF	0.90	0.79	Yes	70.9	2.40	**
	BS	0.91	0.80	Yes	67.0	2.51	**
	PF (k = 0.36)	0.98	1.81	No	34.2	1.20	NS

GM = Geometric, RF = Random-fraction, BS = Broken-stick, PF = Power-fraction
NS, not significant; $^{**}P < 0.01$. [†]Significant positive autocorrelation at 1% significance
[‡]All models were adjusted to number of individuals = 1000

The Durbin-Watson test showed that all models except the Power-fraction model for all classes and the Geometric model in class A had positive autocorrelations of residuals. The Geometric model presented one case (class G) with an inconclusive *d* value at the 1% significance level, whilst the Power-fraction model had an inconclusive *d* value for three classes (A, E and F).

For a fair comparison of the RSD values, all the models were adjusted to give 1000 individuals. RSD values had similar trends to R^2_{adj} values. The smallest RSD values were given by the Power-fraction model in all but classes A and E. The Broken-stick and Geometric models showed the second smallest RSD values. The greatest values for RSD were attained, in all classes, by the Random-fraction model.

The null hypothesis of the Kolmogorov-Smirnov test was that the cumulative probability function of the observed data was the same as that of the modelled data. Only the Power-fraction model showed non-significant differences in all classes. The Broken-stick model showed non-significant differences in all but class G. All the accumulative probabilities obtained with the Random-fraction model were significantly different ($P < 0.01$) in all five classes. The Geometric model achieved a non-significant difference ($P < 0.01$) only in class A and F.

The Power-fraction model attained the overall best fit, except for with class A where the Geometric model did so. The goodness-of-fit assessed with R^2_{adj} and RSD for both the Broken-stick and Geometric model was generally high, although the latter performed poorly with the Kolmogorov-Smirnov test, and both showed positive autocorrelation of residuals (excluding class A, where the Geometric model did not show positive autocorrelation).

As the best fitting model of the RAD of class A, the Geometric model was selected for calculating the coefficients for the DWR method, whilst the Power-fraction model was selected for classes B to G. Thus, the Geometric model was run with m value of 0.81 for class A, and the Power-fraction model was applied with *k* values of 0.61, 0.58, 0.44, 0.35, 0.73 and 0.36 given for classes B to G respectively. In Tokeshi's (1996) original work, it was suggested that the majority of ecological communities could be represented by *k* values in the Power-fraction model between 0 and 0.2. Discrepancies in the *k* values found in the current study could be due to the criteria applied during sampling, which restricted the type of vegetation sampled. Development of RAD models have followed ecological considerations, whilst the sampling methodology applied in the current study was related to grazing and carrying capacity situations, which set aside species such as lichens, moss and fungi. The absence of these species in the total count of individuals will produce RADs different to those that estimate all the individuals in the community. Furthermore, Sutherland (1996) indicated that the PQ method is not very efficient in detecting the rarest species in a plant community, which could be a contributing factor to the difference in the *k* values produced by the Power-fraction model in this study. For the scope of this study, the RAD models are used solely for their mathematical ability to represent the distribution of species within a plant community.

DWR method coefficients

Table 4-6 shows the value of the coefficients (m_q) obtained with the Geometric and Power-fraction models in their respective classes. Some authors suggest that the RAD of species in a plant community can be satisfactorily explained either with vegetation cover data or with biomass data (Goodall, 1952; Jonasson, 1988; Chiarucci *et al.*, 1999), and that both distributions are strongly correlated. Therefore in the current study it was assumed that the models satisfactorily represented the abundance distribution of species in terms of biomass. This assumption was important in integrating RAD models with the DWR method, since the ranking process of the latter is based on the relative biomass of each species within the sampling quadrat. In contrast to the original DWR method where only the three most abundant species are ranked, the methodology of this study ranked from nine to twelve most abundant species. The number of ranks assigned was determined by the number of species found in each single quadrat, such that all the species found in a quadrat were ranked. The number of ranks utilised in the methodology was adequate to explain the distribution of the total number of species found in each vegetation class, between 27 and 90. However, the importance of designing an adequate sampling strategy to ensure that the majority of species are included in the readings must be stressed. In this study, the DWR method reported the presence of the 97.6% of the species recorded by the PQ method, and for the tests described below, the species that were not present in both methods were discarded. This discrepancy in the number of species recorded was attributed to sampling error.

As a first step to test the DWR results, Lin's concordance correlation coefficient (ρ_c) evaluated the agreement between the DWR method results and the botanical compositions produced by the RAD models by measuring the variation from the 45° line through the origin (the concordance line). To do so, botanical composition data were transformed using the arcsine transformation of percentages (Zar, 1999). High reproducibility of the RAD models by the DWR for the seven classes is indicated by ρ_c presented in

Table 4-7. The closer ρ_c is to unity, the better the correspondence between the DWR method and the Power-fraction model. Table 4-7 also shows the bias correction factor (C_b) that measured how far the best fitting line deviated from the 45° concordance line (Lin, 1989). A satisfactory 1:1 correspondence was achieved between the DWR method and the RAD models in all classes. The highest correspondence was found in class F, whilst class E attained the lowest values for both ρ_c and C_b.

Table 4-6 Coefficients for the DRW method (m_q) derived from the Geometric model for class A, and 10000 runs of the Power-fraction model for classes B to G

Rank	Class A	Class B	Class C	Class D	Class E	Class F	Class G
1st	0.224	0.302	0.321	0.330	0.401	0.286	0.377
2nd	0.181	0.186	0.194	0.190	0.213	0.182	0.208
3rd	0.147	0.133	0.136	0.131	0.136	0.134	0.135
4th	0.119	0.101	0.101	0.097	0.092	0.103	0.094
5th	0.096	0.077	0.076	0.073	0.063	0.080	0.067
6th	0.078	0.060	0.058	0.055	0.043	0.064	0.047
7th	0.063	0.046	0.043	0.042	0.028	0.049	0.032
8th	0.051	0.035	0.031	0.031	0.016	0.038	0.021
9th	0.041	0.026	0.021	0.022	0.007	0.028	0.012
10th	–	0.018	0.013	0.015	–	0.019	0.006
11th	–	0.011	0.006	0.009	–	0.012	–
12th	–	0.005	–	0.004	–	0.006	–

Table 4-7 Lin's concordance correlation coefficient (ρ_c) with bias correction factor (C_b) for dry-weight rank (DWR) method and Power-fraction model, and Spearman's rank-order correlation coefficient (r_s) between DWR and point-quadrat methods for each vegetation class

	Concordance correlation		Spearman's rank-order correlation	
Class	ρ_c	C_b †	r_s	Significance‡
A	0.948	0.956	0.661	**
B	0.965	0.979	0.727	**
C	0.929	0.949	0.578	**
D	0.984	0.993	0.721	**
E	0.859	0.897	0.714	**
F	0.987	0.999	0.903	**
G	0.967	0.986	0.599	**

** $P < 0.01$

† $0 < C_b \leq 1$. The further C_b is from 1, the greater the deviation is from a 45° line through the origin

‡ Monotonic relationship between ranks in both methods

Results for Spearman's rank-order correlation coefficient (r_s) test are also given in Table 4-7 for each class. r_s values exhibited significant correlations ($P < 0.01$) between species' rankings in botanical compositions produced by the DWR and PQ methods. These results indicate that the visual ranking of species with the DWR method satisfactorily agrees with the data recorded with the PQ method, the latter of which has been widely used to perform botanical analyses. Therefore these results suggest that the ranks assigned by the observer in the field were strongly correlated to the ranks that the PQ method, a technique less prone to subjectivity, produced.

Figure 4-3 shows the abundance distribution of species described by the RAD models and the DWR method. Regression analyses between the arcsine transformed data from the DWR method and the RAD models were performed. R^2_{adj} and RSD values from these regressions are indicated in Table 4-8. High R^2_{adj} values were achieved in all classes, with the best fitting values for R^2_{adj} and RSD found in class D and A respectively. The lowest R^2_{adj} value obtained was for classes E and G, whilst the highest RSD value was for class G.

Table 4-8 R^2_{adj} and residual standard deviation (RSD) values for the regression analyses between the arcsine transformation of the botanical composition by class produced by the RAD model and the dry-weight rank method for woodland classes

Vegetation class	R^2_{adj}	RSD
A	0.984	0.364
B	0.983	0.509
C	0.984	0.407
D	0.987	0.412
E	0.972	0.805
F	0.974	0.731
G	0.972	0.882

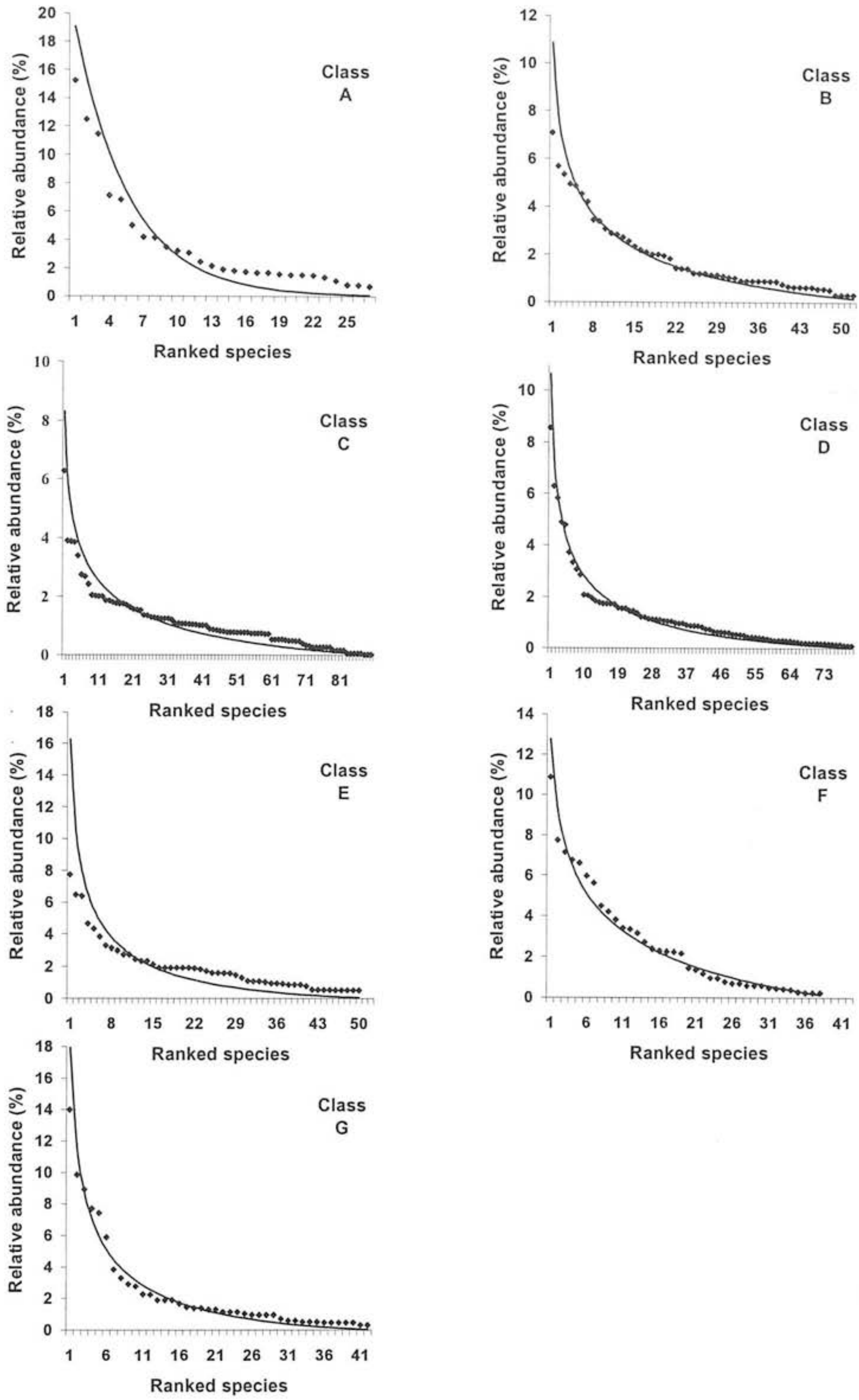


Figure 4-3 Relative abundance distribution of species in each woodland class as produced by the RAD model (—) (Geometric model for class A and the Power-fraction model for classes B to G) and the dry-weight rank method (◆)

The effect of woodland class characteristics on the goodness-of-fit indicators was assessed with the Pearson's correlation coefficient (r) including biomass values reported in next chapter (Section 5.2) and Shannon diversity index of section 4.4 (Table 4-13). The results showed a poor positive value ($r = 0.643$, $P < 0.15$) between the RSD and the biomass values and a poor negative correlation ($r = -0.534$, $P < 0.25$) between R^2_{adj} and biomass values. Regarding Shannon indexes, a poor negative correlation ($r = -0.295$, $P < 0.55$) and an also poor but positive correlation ($r = 0.429$, $P < 0.35$) were found between the RSD and R^2_{adj} values respectively. Although non-significant, the correlations between the goodness-of-fit indicators and the biomass values might suggest that the accuracy of the DWR method was affected by the presence of bulk density of plant material, which could bias the ranking of species by the observer. On the other hand, the correlations between the goodness-of-fit indicator values and the Shannon indexes suggests that the DWR method works better in plant communities with higher diversity indexes. The Shannon index is a measure of heterogeneity, which takes both evenness and species richness into account (Magurran, 1988), and higher values of the index reflect a higher degree of evenness (distribution of species abundances among species). This might suggest that the correct assignment of ranks in the field can be confounded by low numbers of individuals for some species, along with unevenness of their distribution in the plant community. A poor fit can originate not only from errors perpetrated during field sampling, but also from difficulties in fitting RAD models to the original botanical compositions.

Number of ranks scored

Seven different sets of botanical compositions, one per each vegetation class, were produced by progressively reducing the value of ranks scored (*Q*). Seven botanical compositions comprised the set for class A (*Q* ranging from nine to three), ten for class B (*Q* ranging from 12 to three), nine for class C (*Q* ranging from 11 to three), ten for class D (*Q* ranging from 12 to three), seven for class E (*Q* ranging from nine to three), ten for class F (*Q* ranging from 12 to three), and eight for class G (*Q* ranging from ten to three). DWR coefficients (m_q) for Equation (4-2) were produced by averaging the results of 10000 runs of the Power-fraction model. Table 4-9 shows the m_q values for each set of botanical compositions.

Quality of fit of the DWR method to the RAD models within sets was compared through regressions using the arcsine transformation of percentages, giving RSD values for each of the seven sets. Figure 4-4 shows that the lowest RSD value in all seven classes was found at the maximum value of *Q*. In comparison, RSD values increased as *Q* approached three. However, RSD values did not reflect considerable changes when the highest *Q* value was reduced by two or three units. The impact on the percentage of species recorded is also illustrated in Figure 4-4. As the number of ranks scored increased, the DWR method was able to represent a larger number of species, recording an average of 90.44 % (s.e. = 2.3) of the total species when *Q* equalled seven across all classes. There was no difference in the total number of species recorded in classes B and F when *Q* equalled ten, 11 and 12. On the other hand, in classes A, C, D, E and G, a decrease of one in the maximum value of *Q* had an impact in the total number of species recorded. There was a clear trade-off between the effort and time invested in the ranking process and the quality of the output produced. The selection of the final number of ranks that are scored depends on both the level of accuracy that suits the objectives of the research, and the resources and time that are available.

Although the degree to which variations in *Q* affect RSD values was influenced by the original quality of fit of the PQ data to the Power-fraction model, it was the number of species recorded by the DWR that is more sensitive to such variations in *Q*. The sensitivity of the number of species recorded is affected by the degree of dominance that the most abundant species exert on the plant community. Such a degree of dominance was indicated by the parameter *m* and *k* of the Geometric and Power-fraction models respectively. Small values of *m* and *k* indicated high dominance of few species, whilst high *m* and *k* values represented a more evenly distributed plant community. This effect was reflected, for example, in the differences of m_q values across *k* values between classes E and F (with the smallest and largest *k* values respectively) for large values of *Q* (Table 4-9). Scott (1986) showed that the value for the DWR coefficients originally obtained by 't Mannetje and Haydock (1963), emulated a Geometric model with $m = 0.32$. This *m* value obtained for grassland plant communities diverges from the *m* value obtained in woodland class A (0.81), the latter representing a more diverse, low-dominance plant community. Adjustments in the values of the DWR coefficients due to the dominance exerted by the most abundant species have been proposed by Scott (1986) and Nijland (2000). The *m* and *k* values for the RDA models in this study were representing highly diverse plant communities, where the dominance percentage of the most dominant species was 9 – 18 % (Figure 4-3), whilst in grasslands that figure can be more than 80 % (Nijland, 2000). The assemblage of species in plant community ecology that determine the RAD will therefore have to be reflected in the way the DWR method is applied. Scott (1986) has also highlighted the importance of adjusting the number and value of ranks according to the ecology of plant communities.

4.3.9 Conclusions

The results of this work showed that it is feasible to extend the application of the DWR method to plant communities with a higher number of species than the traditional grassland swards to which this method has been applied, such as forest understorey vegetation. To do so, it is necessary to know the mathematical function that explains the abundance distribution of species in the community under study. This function can subsequently be applied to derive the appropriate coefficients for the DWR method according to the number of species ranked during field sampling. The number of ranks to be scored will depend on the level of accuracy needed by the researcher. It has been shown in this work that there is a trade-off between the number of ranks scored and the quality of the data produced by the DWR method. Although in this work, the methodology was developed for montane understorey vegetation, it is likely to be feasible for other plant communities with a high diversity of species. As with the original work of 't Mannetje and Haydock (1963), special care in appropriate training of the observers is required. Despite the time and effort involved in adjusting the model for each particular understorey plant community, this methodology stands as a useful non-destructive alternative for agricultural research and monitoring in plant communities different from grassland swards.

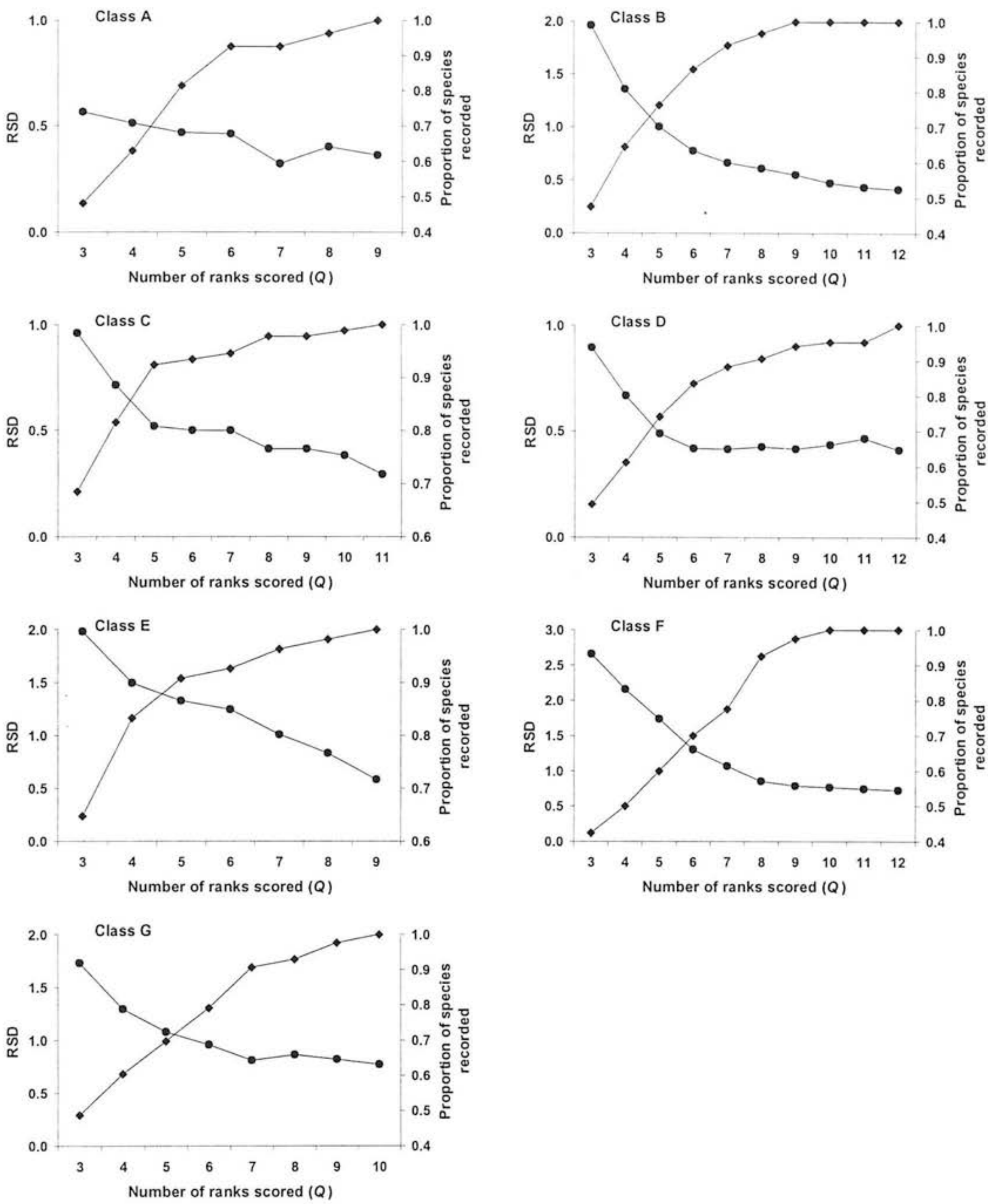


Figure 4-4 Relationships between residual standard deviation (●) and proportion of species recorded (◆) with different number of ranks scored (Q) when fitting the dry-weight rank botanical compositions to the RAD model for each woodland class

Table 4-9 Coefficients for the dry-weight rank method for Q values ranging from Q_{max} to Q = 3 in each woodland class

		m_q											
Class	Q	1	2	3	4	5	6	7	8	9	10	11	12
A	9	0.224	0.181	0.147	0.119	0.096	0.078	0.063	0.051	0.041			
(m = 0.81)	8	0.233	0.189	0.153	0.124	0.100	0.081	0.066	0.053				
	7	0.246	0.200	0.162	0.131	0.106	0.086	0.070					
	6	0.265	0.214	0.174	0.141	0.114	0.092						
	5	0.292	0.236	0.191	0.155	0.126							
	4	0.334	0.270	0.219	0.177								
	3	0.405	0.328	0.266									
B	12	0.301	0.185	0.133	0.101	0.078	0.060	0.046	0.035	0.026	0.018	0.011	0.005
(k = 0.61)	11	0.317	0.193	0.137	0.102	0.077	0.058	0.044	0.031	0.022	0.013	0.006	
	10	0.336	0.200	0.140	0.102	0.076	0.056	0.040	0.027	0.017	0.008		
	9	0.357	0.210	0.143	0.102	0.073	0.051	0.034	0.021	0.010			
	8	0.380	0.218	0.146	0.101	0.069	0.046	0.027	0.012				
	7	0.411	0.229	0.147	0.097	0.063	0.037	0.016					
	6	0.443	0.241	0.148	0.092	0.053	0.024						
	5	0.490	0.250	0.145	0.080	0.035							
	4	0.547	0.263	0.135	0.056								
	3	0.623	0.270	0.107									
C	11	0.323	0.192	0.136	0.101	0.076	0.058	0.043	0.031	0.021	0.013	0.006	
(k = 0.58)	10	0.338	0.201	0.140	0.102	0.075	0.055	0.039	0.026	0.016	0.007		
	9	0.359	0.210	0.143	0.102	0.072	0.051	0.034	0.020	0.009			
	8	0.383	0.219	0.145	0.100	0.069	0.045	0.027	0.012				
	7	0.413	0.229	0.147	0.096	0.062	0.036	0.016					
	6	0.446	0.239	0.148	0.092	0.052	0.023						
	5	0.489	0.252	0.145	0.079	0.035							
	4	0.548	0.262	0.135	0.056								
	3	0.627	0.268	0.105									
D	12	0.331	0.191	0.132	0.097	0.073	0.055	0.041	0.031	0.022	0.015	0.009	0.004
(k = 0.44)	11	0.346	0.198	0.134	0.097	0.071	0.053	0.039	0.027	0.018	0.011	0.005	
	10	0.364	0.204	0.137	0.097	0.070	0.050	0.035	0.023	0.014	0.006		
	9	0.382	0.213	0.140	0.096	0.067	0.046	0.030	0.018	0.008			
	8	0.408	0.219	0.141	0.094	0.063	0.041	0.023	0.010				
	7	0.431	0.229	0.143	0.092	0.058	0.033	0.015					
	6	0.466	0.238	0.142	0.086	0.048	0.021						
	5	0.509	0.247	0.138	0.074	0.031							
	4	0.563	0.256	0.128	0.053								
	3	0.632	0.265	0.103									

Table 4-9 (*Continued*)

		m_q											
Class	Q	1	2	3	4	5	6	7	8	9	10	11	12
E	9	0.400	0.214	0.137	0.092	0.063	0.043	0.028	0.016	0.007			
(k = 0.35)	8	0.423	0.220	0.137	0.091	0.059	0.038	0.022	0.010				
	7	0.447	0.230	0.138	0.087	0.054	0.031	0.013					
	6	0.478	0.238	0.138	0.082	0.045	0.019						
	5	0.519	0.246	0.134	0.071	0.030							
	4	0.569	0.254	0.126	0.051								
	3	0.640	0.259	0.102									
F	12	0.287	0.182	0.134	0.103	0.080	0.063	0.049	0.038	0.028	0.019	0.012	0.006
(k = 0.73)	11	0.302	0.190	0.137	0.104	0.080	0.061	0.047	0.034	0.024	0.015	0.007	
	10	0.322	0.198	0.141	0.104	0.079	0.059	0.042	0.029	0.018	0.008		
	9	0.340	0.208	0.145	0.106	0.077	0.055	0.037	0.023	0.011			
	8	0.366	0.217	0.148	0.104	0.073	0.049	0.029	0.014				
	7	0.393	0.230	0.151	0.102	0.067	0.039	0.018					
	6	0.430	0.241	0.152	0.096	0.056	0.025						
	5	0.475	0.254	0.150	0.084	0.037							
	4	0.537	0.265	0.139	0.059								
	3	0.622	0.271	0.107									
G	10	0.377	0.207	0.135	0.094	0.067	0.047	0.033	0.021	0.013	0.006		
(k = 0.36)	9	0.397	0.214	0.137	0.093	0.064	0.043	0.028	0.016	0.007			
	8	0.419	0.221	0.139	0.091	0.060	0.038	0.022	0.010				
	7	0.445	0.230	0.139	0.088	0.055	0.031	0.014					
	6	0.477	0.237	0.138	0.082	0.046	0.020						
	5	0.519	0.245	0.135	0.071	0.030							
	4	0.570	0.254	0.124	0.052								
	3	0.642	0.258	0.101									

m = parameter of the Geometric model; k = parameter of the Power-fraction model, Q = number of ranks recorded, m_q = coefficient associated with the rank

4.4 Botanical composition results for Coajomulco's grazing areas

A total of 197 different plant species were recorded during sampling. The botanical composition results reported below were produced with the modified DWR described in the previous section for the seven woodland classes, whilst for the grass and scrub class only the point quadrat method (section 4.3.3) was performed. Plant specimens were identified with the assistance of the staff of the Institute of Biology's botanical gardens, National Autonomous University of Mexico.

Plant species were grouped according to an adaptation of the growth habits classification of USDA-NRCS (2001). Thus, the growth habits of the recorded plant species were classified as forb/herb, vine, graminoid, shrub or tree/shrub. Table 4-10 indicates the results for this classification and a brief description of each category. Table 4-11 shows the most abundant species recorded. Each plant species included in this table accounted for more than 5 % abundance in the plant community of at least one vegetation class. The total number of species recorded was grouped in 47 botanical families. Table 4-12 presents an inventory of botanical families indicating the number of species in each family by vegetation class.

Table 4-10 Classification of recorded species according to their growth habits

Growth Habit	Percentage	Description
Forb/herb	52.2 %	Vascular plant without significant woody tissue above or at the ground (ferns are also included).
Vine	7.0 %	Twining/climbing plant with relatively long stems, can be woody or herbaceous.
Graminoid	11.3 %	Grasses and grass-like plant like sedges (Cyperaceae)
Shrub	21.7 %	Perennial, multi-stemmed woody plant that is usually less than 4 to 5 metres in height.
Tree/shrub	7.8 %	Perennial, woody plant with a single stem, normally greater than 4 to 5 metres, but recorded at field sampling with a shrub-height.

Table 4-11 Plant species with more than 5 % abundance in at least one vegetation class

Family	Species
Asteraceae	Baccharis conferta Kunth.
	Cirsium jorullense H.B.K.
	Dalia coccinea Cav.
	Stevia Cav.
	Tagetes erecta L.
Buddlejaceae	Buddleja sessiliflora Kunth
Caryophyllaceae	Arenaria lanuginosa (Michx.) Rohrb.
	Stellaria ovata Willd.
Cyperaceae	Bulbostylis Kunth.
Fabaceae	Trifolium repens L.
Poaceae	Bromus carinatus Hook. & Arn.
	Festuca amplissima Rupr.
	Muhlenbergia robusta (Fourn.) Hitchc.
	Panicum L.
	Pennisetum clandestinum Hochst. ex Chiov.
	Stipa ichu (Ruíz et Pavón) Kunth
	Vulpia myuros (L.) K.C. Gmel.
Rosaceae	Alchemilla procumbens Rose
	Rubus sp. (Tourn.) L.
Scrophulariaceae	Penstemon campanulatus (Cav.) Willd.
Valerianaceae	Valeriana urticifolia Kunth

Table 4-12 Botanical composition of vegetation classes in Coajomulco by family

	Number of species							
Family	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**G&S***
Anemiaceae	1	–	1	–	–	–	–	–
Apiaceae	–	–	1	–	–	–	–	–
Aristolochiaceae	–	–	–	1	1	–	–	–
Asclepiadaceae	–	–	1	1	–	–	–	–
Asteraceae	6	6	12	9	6	4	3	4
Begoniaceae	1	–	2	1	–	–	1	–
Betulaceae	–	–	1	–	–	–	1	–
Brassicaceae	–	–	1	1	–	–	–	–
Buddlejaceae	2	3	3	2	2	1	1	1
Caryophyllaceae	1	1	2	1	2	1	2	1
Cistaceae	–	1	2	1	–	1	1	–
Commelinaceae	2	2	3	3	1	2	1	2
Convolvulaceae	–	–	1	1	1	–	–	–
Crassulaceae	–	1	1	1	–	–	–	1
Cucurbitaceae	–	2	2		1	–	1	–
Cyperaceae	–	1	3	2	1	–	–	–
Dryopteridaceae	–	1	–	1	–	–	–	–
Ericaceae	–	1	1	–	–	–	–	–
Euphorbiaceae	1	2	1	2	–	–	–	–
Fabaceae	–	2	4	6	2	3	2	3
Fagaceae	1	–	2	1	–	–	1	–
Garryaceae	–	1	1	1	2	–	–	–
Gentianaceae	–	–	–	2	1	–	1	–
Geraniaceae	–	1	2	1	2	–	2	1
Grossulariaceae	–	–	1	1	–	1	–	–
Iridaceae	–	–	1	1	–	–	–	1
Lamiaceae	–	3	2	2	2	1	2	3
Liliaceae	–	–	3	1	–	1	–	1
Melanthiaceae	–	–	–	1	–	–	–	–
Onagraceae	1	–	2	1	1	1	1	–
Orchidaceae	–	1	1	2	1	–	–	–
Oxalidaceae	–	–	2	1	–	1	–	1
Passifloraceae	–	–	1	1	1		1	2
Piperaceae	–	1	2	–	1	1	1	1
Poaceae	3	4	5	5	2	5	3	8
Polygonaceae	–	–	3	3	–	1	–	1

Table 4-12 *Continued*

	Number of species							
Family	A	B	C	D	E	F	G	G&S*
Pteridaceae	1	1	3	4	1	1	1	1
Ranunculaceae	–	1	1	2	2	–	1	–
Rosaceae	1	2	3	2	2	1	2	1
Rubiaceae	1	2	2	2	1	1	–	–
Salicaceae	–		1	1	3	2	2	1
Scrophulariaceae	1	2	1	1	2	1	1	–
Solanaceae	–	1	2	1	2	2	2	1
Theaceae	–	–	2	1	–	1	1	1
Tiliaceae	–	–	1	3	1	2	1	–
Valerianaceae	1	1	3	1	1	1	3	2
Violaceae	–	–	1	1	–	–	–	–
Total species	**24**	**44**	**90**	**76**	**45**	**36**	**39**	**38**

*Grass and scrub class

4.4.1 Biodiversity analysis

Species richness

For each of the vegetation classes an estimate of the diversity of plant species was made. The simplest measure of biodiversity is that which compares numbers of species. When estimating the number of species present from sampled data, it is known that the number of species increases with the sample size and sampling effort (Magurran, 1988). Although the effort was constant during the sampling method, the samples were not taken from exactly the same area, but from different randomly selected sites within the vegetation classes, as described in section 4.3.1. The number of sample sizes for each of the vegetation classes were shown to be statistically different ($F = 8.78$, $P < 0.01$). If a direct comparison of species richness were made, it may therefore have been influenced by the size of the sample in each class. To overcome this problem, the data were transformed using the technique of rarefaction (Hurlbert, 1971).

$$E(S) = \sum \left\{ 1 - \left[\binom{N - N_i}{n} / \binom{N}{n} \right] \right\} \qquad (4\text{-}3)$$

where,

$$\binom{N}{n} = \left[\frac{N!}{n!(N/n)!} \right]$$

E(S) was the expected number of species; n was the standardised sample size; N was the total number of individuals sampled; and N_i was the total number of individuals in the *i*-th species.

Since class A had the smallest sampling area, it was used as the standarised sample size (n) in the rarefaction method. The adjusted number of plant species after rarefaction is shown in Table 4-13.

Diversity index

Indices based on the proportional abundance of species provide an alternative measure of diversity to those that consider only taxa richness. The Shannon index of diversity (Shannon and Weaver, 1949) is based on the proportional abundance of species, indicating also the degree of evenness in the species distribution. It is calculated from:

$$H' = -\sum p_i \ln p_i \qquad (4-4)$$

where, H' was the index of diversity; and p_i was the proportion of individuals found in the i-th species.

Shannon indexes derived for each vegetation class are shown in Table 4-13. Differences in diversity values H' between vegetation classes were assessed with the t-test adapted for the Shannon index by Magurran (1988).

Table 4-13 Rarefacted species richness and Shannon diversity index in each vegetation class

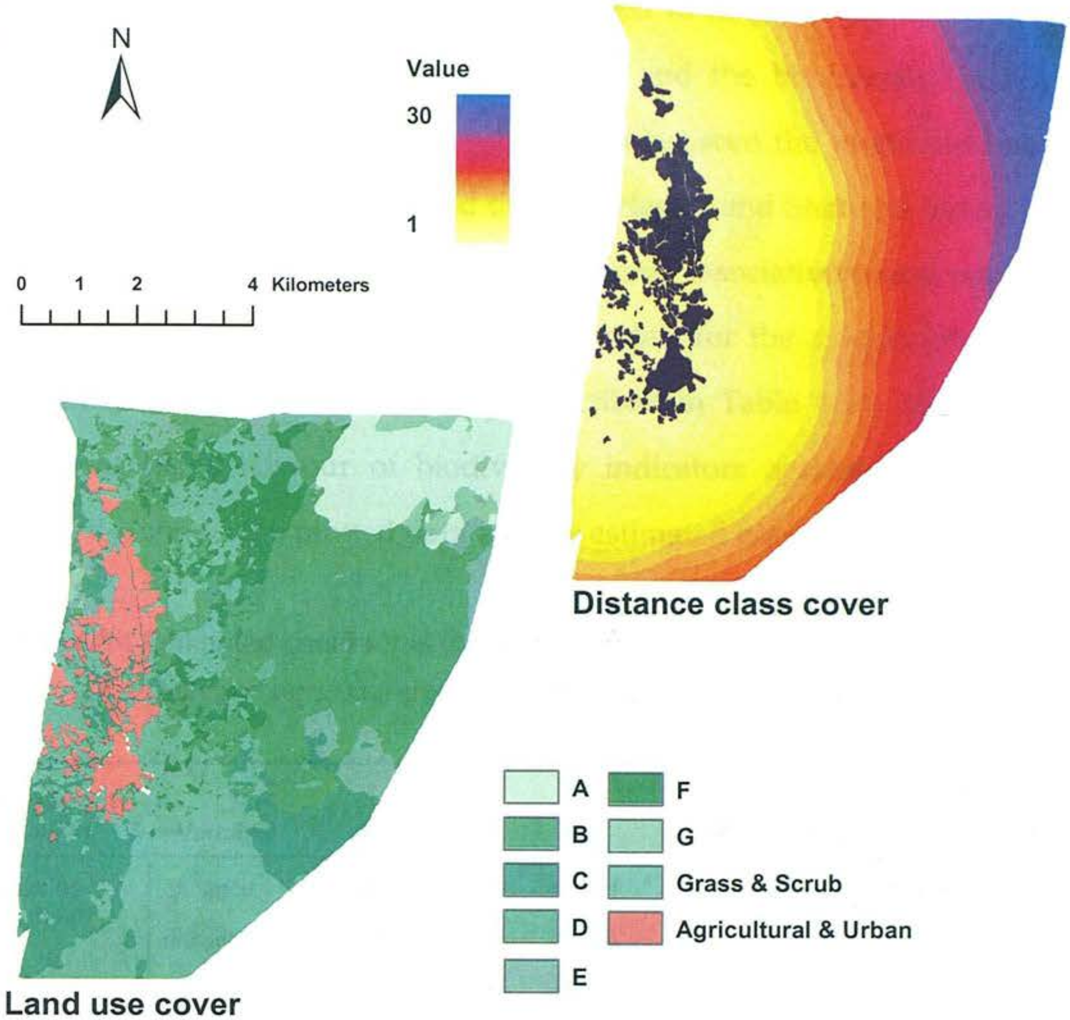
Vegetation Class	Species richness (rarefacted)	Shannon index*
Woodland A	27.0	2.71^{a}
Woodland B	45.7	3.53^{b}
Woodland C	68.9	3.88^{c}
Woodland D	56.5	3.82^{c}
Woodland E	40.9	3.31^{d}
Woodland F	30.8	3.10^{e}
Woodland G	37.5	3.13^{e}
Grass & Scrub	28.4	2.70^{a}

*Different superscript are significantly different

4.4.2 Spatial analysis of diversity indicators

Further analysis was carried out to find out any evidence of an effect of anthropogenic disturbance on the biodiversity indicators of the plant communities derived in the previous section. Although no direct measurement of anthropogenic disturbance was undertaken, it was assumed that its effect was inversely related to the distance of the plant communities from the urban and agricultural area. It was also assumed that sheep grazing was the main source of disturbance, although activities like herb, dead wood and leaf litter collection, and recreational activities would also have been contributing factors. Illegal activities like soil extraction and charcoal making were also present.

Spatial analysis was performed on the land class cover presented in Figure 4-2. Thirty concentric bands were produced around the urban and agricultural area. Each equidistant band represented an increasing distance of approximately 225 m from the central point. The bands covered the total parish area of Coajomulco (Figure 4-5). Both the averaged rarefacted number of species value and the Shannon index were calculated for each distance band using a zonal statistics procedure in the GIS. These results are also included in Figure 4-5 .



Distance class	Number of species $\bar{X}$	Number of species s.e.	Shannon index $\bar{X}$	Shannon index s.e.	Distance class	Number of species $\bar{X}$	Number of species s.e.	Shannon index $\bar{X}$	Shannon index s.e.
1	46.1	0.066	3.31	0.002	16	44.4	0.087	3.38	0.003
2	47.9	0.088	3.42	0.003	17	42.6	0.081	3.34	0.003
3	46.3	0.092	3.40	0.003	18	40.1	0.066	3.28	0.003
4	44.4	0.091	3.33	0.003	19	39.7	0.071	3.26	0.003
5	41.8	0.090	3.22	0.003	20	39.2	0.076	3.24	0.003
6	40.6	0.086	3.20	0.003	21	38.9	0.077	3.23	0.003
7	43.3	0.089	3.30	0.003	22	38.6	0.079	3.21	0.003
8	44.8	0.086	3.38	0.003	23	36.9	0.086	3.13	0.004
9	44.8	0.081	3.38	0.003	24	35.0	0.081	3.05	0.004
10	45.1	0.079	3.39	0.003	25	35.4	0.086	3.06	0.004
11	45.1	0.075	3.40	0.002	26	32.5	0.092	2.94	0.004
12	45.5	0.081	3.40	0.003	27	29.5	0.070	2.81	0.003
13	46.1	0.086	3.41	0.003	28	27.4	0.039	2.72	0.002
14	48.2	0.087	3.50	0.002	29	27.0	0.000	2.71	0.000
15	46.9	0.089	3.46	0.002	30	27.0	0.000	2.71	0.000

Figure 4-5 Spatial analysis for the assessment of biodiversity indicators by increase of distance from the agricultural and urban class

Pearson's correlation coefficient (r) was used to find out the existence of a linear association between distance bands and the biodiversity indicator. Significant negative correlations were found between the rarefacted number of species (r = -0.86, $P < 0.01$) and distance classes and Shannon indexes and distance classes (r = -0.762, $P < 0.01$). The linear association found out with r preceded the exploration of regression models for the association of these variables. A quadratic relationship, described in Table 4-14, was found to represent the behaviour of biodiversity indicators against distance class. Figure 4-6 shows the plotted data and the estimated curve.

Table 4-14 Estimated coefficients for the quadratic relation between distance from urban and agricultural areas and biodiversity indicators

Biodiversity indicator	Variable	B	t	Sig.	R^2	R^2_{adj}	ANOVA F	ANOVA Sig.
Species richness	distance	0.662	3.76	<0.001	0.908	0.901	132.90	<0.001
	distance^2	-0.041	-7.48	<0.001				
	(constant)	43.108	36.38	<0.001				
Shannon index	distance	0.040	6.40	<0.001	0.909	0.902	134.77	<0.001
	distance^2	-0.002	-9.87	<0.001				
	(constant)	3.207	0.04	<0.001				

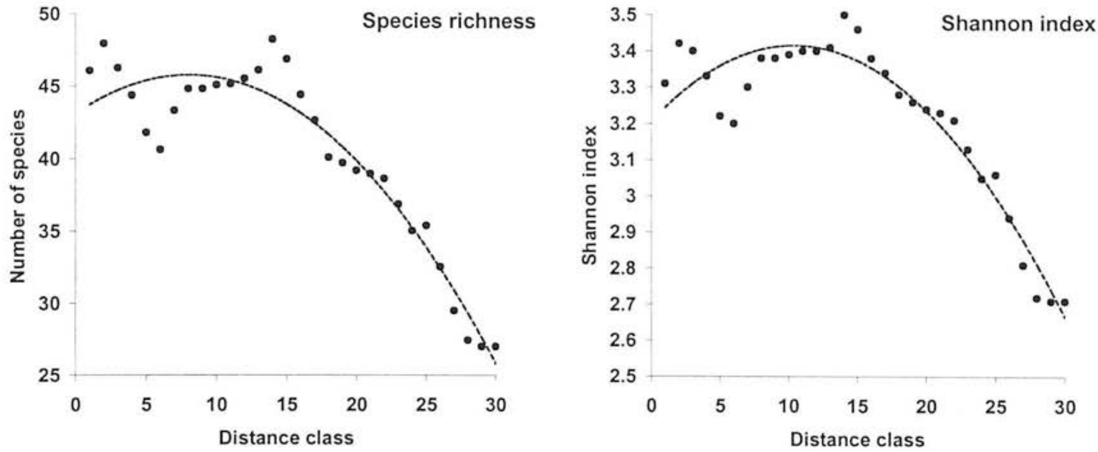


Figure 4-6 Relationship between biodiversity indicators (●) and distance classes with the quadratic model fitted curve (- - -)

Regarding species richness, the statistical evidence indicated that there was a slight increase in the number of species as the distance from the urban and agricultural land expanded until an inflexion point was reached where this relation became inverse. This might suggest that grazing intensity on the urban and agricultural areas' surroundings had a direct effect on the number of species. Grazing and human activities have created a semi-natural habitat in the vicinity of the parish town, whilst natural vegetation covers more distant zones.

As mentioned in Chapter 2, it has been acknowledged that grazing of domestic stock has an effect on the vegetation population in semi-naturals and fragmented habitats. Furthermore, some authors have reported an increase of species diversity in semi-natural habitats due to grazing activities (e.g. Bignal and McCracken, 1996; Kuiters, 1998). It has been suggested that the highest species richness is found at "intermediate" levels of disturbance. However, Kondoh (2001) suggested that the disturbance-diversity relationship can be either negative or positive depending on the specific characteristics of the system. In a review of the impact of grazers on different ecosystems by Proulx and Mazumder (1998) it was concluded that plant species richness decreases with high grazing in nutrient-poor ecosystems, whilst in nutrient-rich ecosystems, high grazing produces an increase in the number of species. Species richness can also be benefited by nutrient-mediated grazing effects where dung deposition plays an important role (Mayle, 1999; Bokdam and Gleichman, 2000; Posse *et al.*, 2000) or by dispersion of reproductive material (Fischer *et al.*, 1996). However, higher values of species richness in grazed habitats are frequently due to the expansion of minor and/or less palatable species (Shurin and Allen, 2001; Wardle *et al.*, 2001). Spatial variation in grazing pressure can produce an increase in diversity by allowing different degrees of grazing-induced conditions to exist simultaneously (Reimoser *et* al., 1999). Although this might be seen as positive in terms of diversity, it can create a vulnerable or less protected system against environmental stress, erosion, or the loss of important species (Gill, 2000; Posse *et al.*, 2000).

Although the Shannon index is indicative of species richness, it also represents a measure of evenness (Magurran, 1988). The outcome of this study supports the finding of Shurin and Allen (2001) that higher disturbance in the immediacies reduced the level of dominance of the most abundant species with the appearance of minor species or competitors. Lower Shannon indexes for more distant habitats can be a reflection of a "steady" stage of the population dynamics exerted by undisturbed dominant species. It can also be noted from Table 4-13 that the lowest Shannon index was obtained in Woodland A and the Grass and Scrub class. Woodland A is the most distant vegetation class to the agricultural and urban class (see Figure 4-6), and by inference, the least disturbed one. On the other hand, the Grass and Scrub class is, in practical terms, the most affected by anthropogenic disturbances. Low and statistically equal Shannon indexes for both classes indicates that in both, undisturbed and highly modified habitats, few plant species exert high dominance.

Chapter 5

Regional Characterisation of Local Grazing resources for Grazing Sheep in Coajomulco. II. Biomass Production and Nutritional Profile

5.1 Introduction

Following with the characterisation of Coajomulco's grazing resources, this chapter focuses on both the phenological characteristics of Coajomulco's plant communities and the nutritional characterisation of the species grazed by sheep flocks. To do so, the chapter is divided into four sections, sections 5.2 and 5.3 look at the measurement of biomass production and regrowth capacity respectively. The identification of edible species is reported in Section 5.4 and the quantification of their nutritional characteristics is reported in the last section.

5.2 Standing biomass production

5.2.1 Methodology

The biomass production sampling was carried out simultaneously with the DWR botanical composition sampling. The sampling strategy was described in Chapter 4 (Section 4.3.1). Once the counting for the DWR was completed, all the plant material included in the sampling unit was carefully harvested by hand. The harvested material consisted of only leaves and young stems, while highly lignified and/or dead material was rejected. The collected material was weighed and subsequently dehydrated at 100 °C for 48 hours to determine its dry-matter content.

A spatial analysis similar to the one described in Chapter 4 (Section 4.4.2) was carried out to find out any relationship between biomass production and disturbance as measured by the distance from the Agricultural and Urban class.

5.2.2 Results and discussion

Table 5-1 shows the biomass production values obtained. Since the sampling took place during the first third of the rainy season, these figures were considered as standing biomass production values.

Table 5-1 Standing biomass production by vegetation class

Vegetation Class	Biomass production*	
	$\bar{x}$	s.e.
Woodland A	492.6	40.3
Woodland B	604.1	29.5
Woodland C	223.4	26.0
Woodland D	492.8	32.9
Woodland E	634.5	49.8
Woodland F	432.3	13.3
Woodland G	760.2	56.7
Grass & Scrub	442.8	31.6

*kg dry-matter ha^{-1}

Biomass production and disturbance

A Pearson's correlation coefficient (r) indicated a highly significant positive correlation between the standing biomass values and distance class ($r = 0.75$, $P < 0.01$). It is important to highlight that the correlation did not find any significant relationship between standing biomass and biodiversity indicators across vegetation classes. However, a significant negative correlation ($r = -0.44$, $P < 0.01$) between standing biomass and species richness was found across the distance class.

As was done for the biodiversity indicators in the previous chapter, a regression analysis was carried out to find out the relationship between biomass and disturbance. A quadratic relationship (described in Table 5-2) was found to represent the effect of distance class on the standing biomass production. Figure 5-1 reveals this relationship.

Table 5-2 Estimated coefficients for the quadratic relation between distance from urban and agricultural areas and standing biomass

	Variable	*B*	*t*	Sig.	R^2	R^2_{adj}	ANOVA *F*	ANOVA Sig.
Standing biomass	distance	15.02	5.98	<0.001	0.739	0.719	38.15	<0.001
	$distance^2$	-0.33	-4.27	<0.001				
	(constant)	387.52	22.97	<0.001				

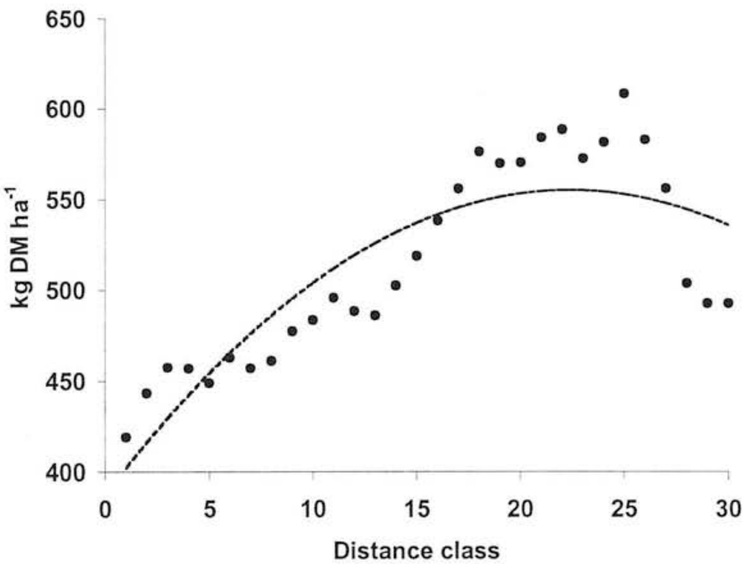


Figure 5-1 Relationship between standing biomass production (●) and distance classes with the quadratic model fitted curve (- - -)

These findings might suggest that as the level of anthropogenic disturbance increases (e.g. grazing pressure on the immediate vicinity of the parish town) there is a reduction in the amount of standing biomass. The quadratic relation between standing biomass and distance class indicates that in more distant areas (less disturbed) the production of standing biomass is simply an indication of the dynamics of the natural habitat.

Integrating the findings of Chapter 4 (Section 4.4.2) with those of this section, the relationship between disturbance, species richness and productivity were shown to be linked dynamically within the habitat. A Pearson correlation coefficient showed, as expected, a negative relationship (r = -0.64, $P < 0.01$) between biomass production and species richness with increasing distance from the Agricultural and Urban class. As concluded by Kondoh (2001), the interactive effects of disturbance and productivity can affect species richness to various degrees. However, Smith (1994) did not report any link between botanical diversity and productivity.

The negative correlation between standing biomass and species richness across distance classes agreed with the "humpback" model of Al-Mufti *et al.* (1977). This model proposed that greatest diversity occurs at low to intermediate levels of productivity. Although some authors have reported similar findings (e.g. Willems, 1983; Oomes, 1992), their works have been developed in grasslands. The relationship found in this study between biomass productivity and species richness is simply inverse linear, without evidence of the "humpback" curve. In addition, it should be remembered that the sampling methodology for biomass of Section 5.2.1 rejected dead material, contrasting with Al-Mufti's (1977) model. The relationship between productivity, biodiversity and disturbance can be seen as site- or habitat-specific (Marrs, 1993; Oba *et al.*, 2001).

5.3 Estimation of plant biomass regrowth

5.3.1 Methodology

Grazing exclusion cages were used to estimate the regrowth capacity of Coajomulco's plant communities. Ten 2 m × 1.5 m-cages were set up throughout the forested area of Coajomulco, whilst five 1 m × 1.5 m-cages were set up in the Grass and Scrub (G&S) class. The selection of the cages' location could not be random since areas far away from the busiest grazing routes had to be chosen in order to guarantee the durability of the cage for all the experiment. Nor was any consideration given to the woodland class where the cages were located. It was acknowledge that this represented a limitation in the methodological procedure, but it was accepted due to time and resources restrictions.

Once a cage had been placed in the selected area, all the plant material within the cage area and up to a height of 1.5 m was carefully harvested by hand. The collection of plant material was very meticulous and, similarly to the biomass production sampling (Section 5.2.1), only leaves and young stems were harvested. The criteria applied for the harvest of material could be regarded as "expert knowledge" of the grazing and browsing action of the local sheep. The collected material was weighed and subsequently dehydrated at 100 °C for 48 hours to determine its dry-matter content. Thirty days after the collection, all the vegetal regrowth in the cages was harvested with the same criteria of inclusion. It was then weighed and dehydrated. All the cages were read for the first time by May, 2000, and seven more monthly readings were made.

The capacity of vegetal regrowth after defoliation was measured as monthly percentage of regrowth according to the equation:

$$G_t\% = \frac{B_t}{B_{t-1}} \qquad (5\text{-}1)$$

where, $G_t\%$ is the estimated regrowth percentage at time *t*, and B is the dry weight of the biomass collected at time *t*. Thus, an averaged regrowth percentage was calculated for both the woodland classes and the G&S class for each month of the grazing season. These averaged regrowth percentages were applied in conjunction with the standing biomass production values of Table 5-1 to produce a biomass production curve for the grazing season.

5.3.2 Results and discussion

Vegetation regrowth

The averaged percentage regrowth for both the woodland class and G&S class is presented in Figure 5-2. A non-parametric Wilcoxon test for two related samples indicated that there was a non-significant similarity ($P > 0.01$) between the regrowth patterns of the woodland and G&S classes. It can be noticed that, excluding the response after the first collection, whilst the regrowth capacity of the woodland class showed a steady decline as the grazing season progressed, the G&S class peaked by September, with a subsequent abrupt decline by the end of the year.

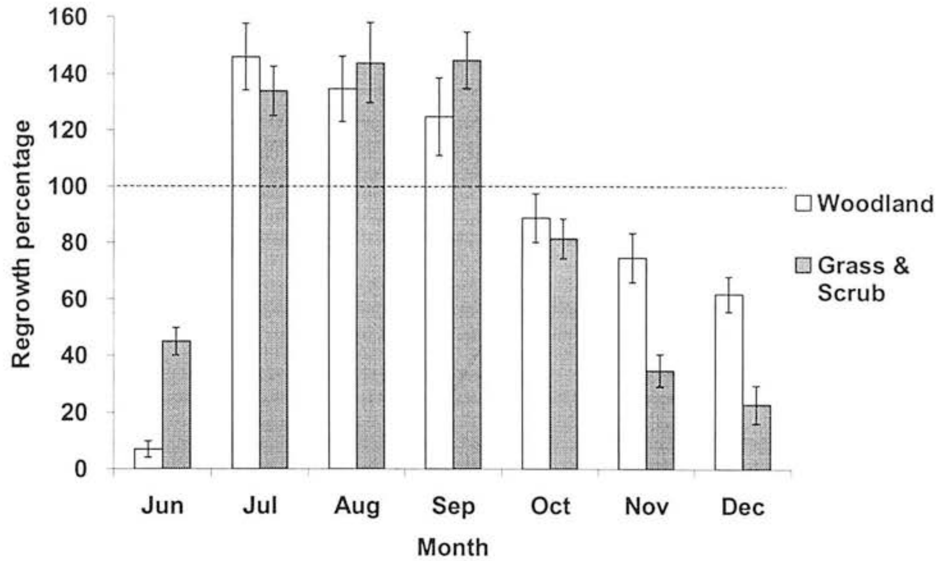


Figure 5-2 Averaged regrowth percentage by vegetation class along the grazing season

The results showed a severe decline in the regrowth capacity of all vegetation by October. In the central part of Mexico, there is an abrupt end to the grazing season around one month after the beginning of the cold and dry winter in November (see Figure 3-2). This phenomenon is partially responsible for the non existence of grazing in communal areas after December (the other reason being the high availability of post-harvest fodder).

It can be assumed that Coajomulco's plant communities are abundant in species whose physiology makes them die back under unfavorable environmental conditions. Raunkiaer (1934) proposed a classification method for plants based on their "life- forms". Of special interest for this discussion are hemicryptophytes (plants that die back after the growing season but propagate through buds at ground level); geophytes (like hemicryptophytes but survive in the form of rhizome, bulb or root); therophytes (annual plants wintering as seeds); and chamaephyte (herbaceous and/or woody and persistent plants) (Royal Botanic Gardens, Kew, 2000). Although there was not sufficient information available to apply Raunkiaer's (1934) classification to the majority of Coajomulco's plant species, it has been reported that hemicryptophytes, geophytes and therophytes dominate the understorey of temperate forests (Valbuena and Trabaud, 1995; Sorensen and Tybirk, 2000). Sorensen and Tybirk (2000) also found out that chamaephytes were replaced by hemicryptophytes and geophytes in the evolution in vegetal succession from heath to forest. Furthermore, it has been reported that grazing in woodland increases the abundance of geophytes (Noy-Meir and Oron, 2001), and hemicryptophytes and therophytes (Debussche *et al.*, 2001). Better understanding of the vegetation dynamics that take place in Coajomulco's plant communities is therefore essential not only in terms of biomass production, but also because it determines the conditions for the beginning of the grazing season and subsequently the sustainability of the grazing activities in the forest.

The regrowth capacity behavior of the G&S class was largely influenced by the presence of kikuyu grass (*Pennisteum clandestinum*) since it was the most dominant species in this class. Both kikuyu's growth vigor in warm and humid conditions, and low tolerance to lack of water and low temperatures is well known (Mears, 1970; Colman and O'Neill, 1978), and its productivity has been characterised for the region (CEIEPO, 1997; González-Estrada, 1998).

Estimation of total biomass production in the grazing season

The estimated total biomass production during the grazing season for each vegetation class is shown in Table 5-3. An estimated biomass production curve for the G&S class was derived from biomass production and regrowth data of natural pastures of CEIEPO (CEIEPO, 1997, 2000, 2001). According to these records 90.5 % of the total biomass production of kikuyu pastures is produced between May and December. This biomass production curve is shown in Figure 5-3. Since there was a lack of knowledge about the relation between woodland classes' biomass production in dry season and grazing season, the same criteria for the G&S class was applied for the derivation of the woodland biomass production curve. Figure 5-3 shows the averaged biomass production for the seven woodland classes.

Table 5-3 Total biomass production during the grazing season by vegetation class

Vegetation Class	Biomass production*
Woodland A	897.4
Woodland B	1100.5
Woodland C	406.9
Woodland D	897.8
Woodland E	1156.0
Woodland F	787.5
Woodland G	1384.9
Grass & Scrub	2503.2

*kg dry-matter ha^{-1}

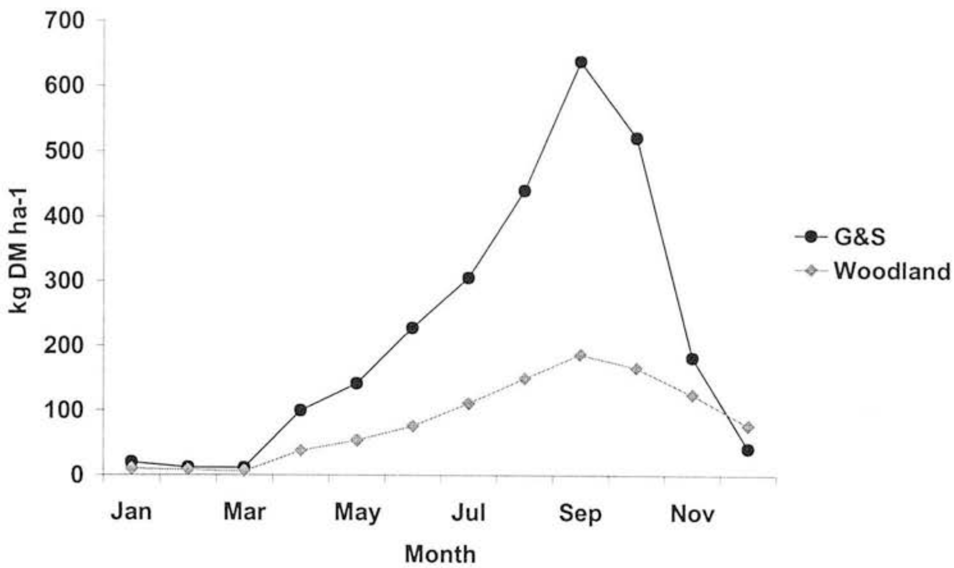


Figure 5-3 Biomass production (dry-matter ha^{-1}) along the year for both the Grass and Scrub class and the woodland classes (averaged)

5.4 Edible species identification

As it was mentioned in Section 4.1, native forage species of Mexico have not been fully characterised by the scientific community. However, this does not mean that local knowledge on the characteristics and utilisation of plant species is non existent. The use of local plants in the cooking, traditional medicine and folklore of current Mexican indigenous communities has been a subject of different studies and reviews (e.g. Bye, 1981; INI, 1994; Ugent, 2000). Unfortunately, few studies have developed both a qualitative and quantitative assessment regarding the role of local plant species as a fodder source. In this context, some useful reviews have been presented by CIDE (2000) and López *et al.* (1985) for grazing resources in Mexican pine and oak forests, whilst Camacho *et al.* (1999) and Nahed *et al.* (1998) have catalogued local resources for sheep grazing in the highlands of Chiapas.

The biodiversity of the plant communities in Coajomulco's grazing areas represented a challenge for the identification of those species that were consumed by local sheep. Thus, a participatory approach was undertaken in which the identification of edible species by sheep relied totally on the farmers' and shepherds' expertise. The conceptual framework for this participatory exercise was based on Cezar's (1999) work that highlights the role of farmers' participation as the way to develop agricultural knowledge information systems.

5.4.1 Methodology

During the botanical composition sampling, specimens were collected to be preserved as reported by MacFarlane (1994). A herbarium was prepared with all the plant species collected. Farmers and shepherds were visited at their homes and were presented with the herbarium. They were asked to identify the plant species that they regarded as edible and non-edible for their sheep. A total of 12 farmers participated in this exercise.

This exercise was complemented with field work during which an observer accompanied a shepherd on his daily herding activities. The observer was assisted by the shepherd in identifying the species grazed or browsed by sheep. This was not a formal methodology to record the plant species consumed by sheep, but was an interactive process in which observer and shepherd jointly made an "inventory" of edible species. This exercise was carried out with five shepherds with spaced visits throughout the grazing season. All the grazing areas identified in Chapter 3 (Section 3.4.4) were visited at least once.

The information collected in these two exercises was complemented with CIDE's (2000) catalogue of plant species with forage use. The abundance of edible species in each vegetation class was derived from the botanical composition data described in Chapter 3. It has been shown that botanical compositions derived from vegetation cover data are strongly correlated with biomass data, and that therefore abundance data can be expressed as biomass values (Goodall, 1952; Jonasson, 1988; Chiarucci *et al.*, 1999). Thus, biomass production data for edible species were derived by directly applying their relative abundance percentages to the biomass production values of Table 5-3 to estimate the yield of edible material in each vegetation class.

5.4.2 Results

A total of 72 plant species were identified as edible by local sheep. All these species were grouped in 30 botanic families, and are listed in Table 5-4. The abundance of edible species by vegetation class, as well as their derived biomass production are shown in Table 5-5. The proportion of edible species in relation to the total number of species is also given.

Table 5-4 Identified edible species by sheep in Coajomulco

Family	Name
Anemiaceae	*Anemia* Sw.
Apiaceae	*Eryngium* L.
Aristolochiaceae	*Aristolochia* L.
Asteraceae	*Archibaccharis* J. D. Jacks.
	Baccharis conferta Kunth.
	Bidens L.
	Cirsium jorullense H.B.K.
	Eupatorium areolare DC.
	Gnaphalium L.
	Melampodium L.
	Pluchea (P. Mill.)
	Rumfordia floribunda DC.
	Senecio L.
	Stevia Cav.
	Tagetes erecta L.
	Taraxacum officinale G.H. Weber ex Wiggers
Betulaceae	*Alnus* P. Mill.
Buddlejaceae	*Buddleja americana* L.
	Buddleja cordata Kunth.
	Buddleja parviflora H.B.K.
	Buddleja sessiliflora Kunth.
Caryophyllaceae	*Stellaria ovata* Willd.
Cistaceae	*Helianthemum glomeratum* (Lag.) Lag. ex Dunal
Commelinaceae	*Commelina coelestis* L.
	Gibasis Raf.
	Tripogandra disgrega (Kunth) Woodson
Convolvulaceae	*Ipomoea purga* (Wender.) Hayne
Crassulaceae	*Sedum* L.
Cyperaceae	*Bulbostylis* Kunth.
	Cyperus L.
Dryopteridaceae	*Woodsia* R. Br.
Fabaceae	*Astragalus* L.
	Cologania biloba (Lindl.)
	Desmodium L.
	Lupinus campestris Cham. Et Schltdl.
	Phaseolus coccineus L.

Table 5-4 *Continued*

Family	Species
Fabaceae (*cont.*)	*Trifolium amabile* Kunth.
	Trifolium repens L.
	Quercus laurina Humb. et Bonpl.
Gentianaceae	*Sabatia* Adans.
Geraniaceae	*Erodium cicutarium* (L.) L'Hér. ex Ait.
	Geranium albidum Rydb.
Lamiaceae	*Lepechinia caulescens* (Ortega) Epling
	Salvia lavanduloides Benth.
	Scutellaria L.
	Stachys coccinea Jacq.
Onagraceae	*Fuchsia microphylla* H.B.K.
Orchidaceae	*Malaxis* Soland. ex Sw.
Passifloraceae	*Passiflora* L.
Poaceae	*Bromus carinatus* Hook. & Arn.
	Festuca amplissima Rupr.
	Muhlenbergia robusta (Fourn.) Hitchc.
	Panicum L.
	Pennisetum clandestinum Hochst. ex Chiov.
	Stipa ichu (Ruíz et Pavón) Kunth
	Vulpia myuros (L.) K.C. Gmel.
Pteridaceae	*Cheilanthes arizonica* (Maxon) Mickel
	Pellaeae ovata (Desv.) Weath.
Ranunculaceae	*Clematis dioica* L.
	Thalictrum L.
Rosaceae	*Alchemilla procumbens* Rose
	Crataegus mexicana Moc. & Sessé
	Prunus capuli Cav.
	Rubus sp. (Tourn.) L.
Rubiaceae	*Bouvardia ternifolia* (Cav.) Schlecht.
	Crusea coccinea D.C.
	Didymaea alsinoides (Cham. & Schltdl.) Standl.
Salicaceae	*Salix paradoxa* H.B.K. var. ajuscana C. K. Schneid.
Scrophulariaceae	*Castilleja tenuiflora* Benth.
	Penstemon campanulatus (Cav.) Willd.
Solanaceae	*Solanum stoloniferum* L.
Valerianaceae	*Valeriana urticifolia* Kunth

Table 5-5 Abundance and derived biomass production of edible species, and proportion of edible species by vegetation class

Vegetation Class	Abundance of edible species	Biomass production of edible species*	Proportion of edible species**
Woodland A	93.8 %	897.4	0.88
Woodland B	82.9 %	1100.5	0.77
Woodland C	69.6 %	406.9	0.43
Woodland D	65.8 %	897.8	0.58
Woodland E	79.8 %	1156.0	0.58
Woodland F	74.2 %	787.5	0.60
Woodland G	73.8 %	1384.9	0.56
Grass & Scrub	80.5 %	2503.2	0.50

*kg dry-matter ha^{-1}

**Calculated as the number of edible species over the total number of species

Further exploration of the results in Table 5-5 showed no significant correlation between biomass production of edible species and the proportion of edible species. This finding suggests, primarily, that the productive potential is directly attributed to each species in particular, but in addition, that edible species as a group have different productive properties depending on the vegetation class in which they are found. Thus, to investigate the relationship between the abundance of edible species and their productivity, a spatial analysis relating the level of anthropogenic disturbance with the distance from the Agricultural and Urban (A&U) class was carried out, similarly to the one described in Section 4.4.2 and 5.2.2. First, a highly significant correlation (r = 0.94, P < 0.01) was found between distance classes and proportion of edible species. Subsequently, the relationship between proportion of edible species and biomass of edible species was evaluated across distance classes. A significant negative correlation (r = -0.87, P < 0.01) across distance classes was found. The linear fit in Table 5-6 describes the relationship between proportion and biomass of edible species shown in Figure 5-4.

Table 5-6 Estimated coefficients for the linear relationship between biomass production of edible species and proportion of edible species

							ANOVA	
	Variable	*B*	*t*	Sig.	R^2	R^2_{adj}	*F*	Sig.
Biomass of edible species	proportion	-1332.1	-9.04	<0.001	0.759	0.749	81.70	<0.001
	(constant)	2062.2	19.67	<0.001				

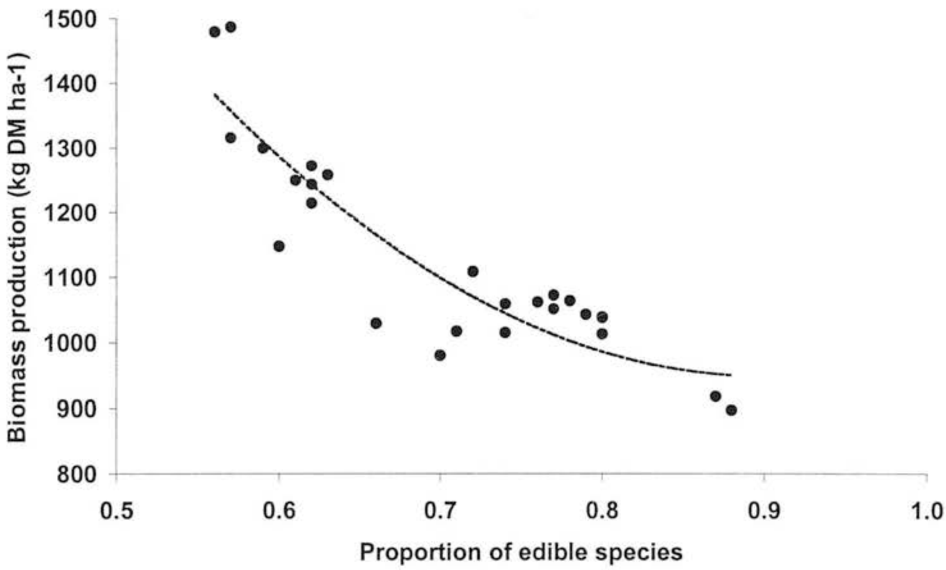


Figure 5-4 Relationship between biomass production (●) and proportion of edible species with the linear model fitted curve (- - -)

The relationships described above suggest that undisturbed habitats have a higher proportion of edible species than disturbed habitats. This can be partly due to the presence of species that, although edible, are not tolerant to grazing, and therefore, in areas with higher grazing pressure will be the first to disappear. Whilst grazing can bring about a reduction in the number of more palatable species (González-Hernández and Silva-Pando, 1996; Wardle *et al.*, 2001), it can also promote higher levels of species richness by reducing plant competition. Thus, the effect of distance from the A&U class on the relative abundance of some families was carried out. Three families whose palatability and tolerance to grazing were relatively well known were chosen: Asteraceae (abundant forbs and herbs with varied palatability), Poaceae (abundant grass species with high tolerance to grazing), and Caryophyllaceae (creeping forb with low tolerance to grazing). Figure 5-5 shows that at low distances from the A&U class the relative abundance of the family Poaceae was higher than the Asteraceae's, whilst the Caryophillaceae's was practically null. On the other hand, as the distance from the A&U class increased, the relative abundance of both the family Asteraceae and Caryophillaceae increased, the latter being more obvious. In contrast, as the level of disturbance lessened, the Poaceae family was found to decrease in abundance.

The relationship between species richness and disturbance was discussed in Section 4.4.2, from which it can be inferred that a minor proportion of edible species is a consequence of higher levels of biodiversity in more disturbed areas (Bokdam and Gleichman, 2000; Kondoh, 2001). The effect of trampling and physical action of the animal in creating an heterogeneous niche for the expansion of other species can also be added (Mayle, 1999; Posse *et al.*, 2000).

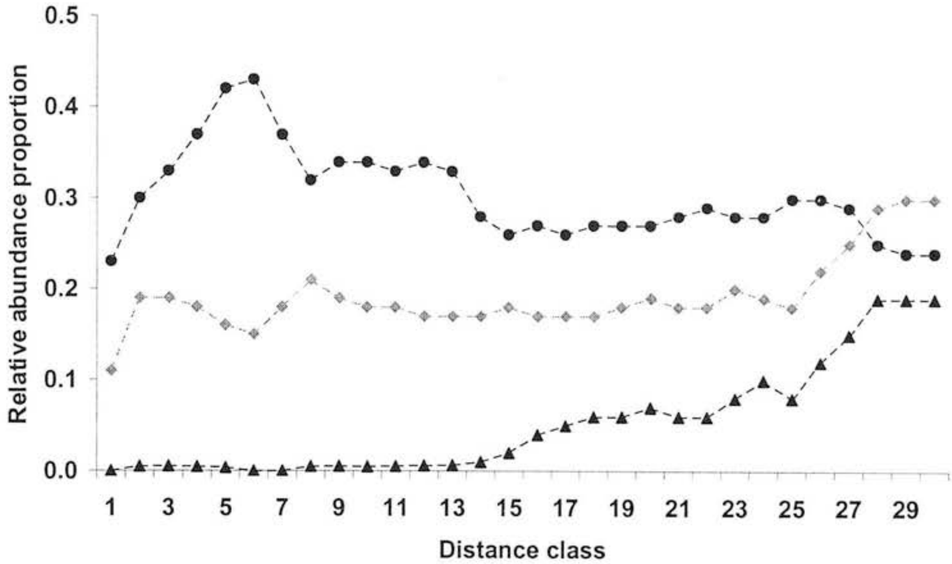


Figure 5-5 Relative proportion of the Asteraceae (◆), Poaceae (●) and Caryophillaceae (▲) families in the edible biomass by distance class from the Agricultural and Urban class

5.5 Nutritional profile of Coajomulco's grazing resources

Most of the data available in Mexico about the nutritional characteristics of feedstuffs for sheep are based on the NRC's (1985) sheep feeding systems. This information has been developed mainly for intensive production systems based on diets with a high grain content. Thus, it is evident that, although some assumptions can be drawn from them, this information is of little utility for the smallholder sheep farming systems that this study considers. Some interesting efforts to characterise the nutritional content of local forages have been reported for the highlands of Chiapas (Camacho *et al.*, 1999), the tropical region of Oaxaca (Arellano *et al.*, 1993), and the arid region of northern Mexico (Ramirez *et al.*, 2000). However, and as has been mentioned throughout this work, the lack of information on nutritional characteristics of local forage species for Coajomulco drove the need to produce grassroots information This section reports the results of the nutritional analysis of Coajomulco's edible species considering both the nutritional profile and the degradation kinetics of their fibre content.

5.5.1 Methodology

Collection of forage samples

All the 72 plant species that were identified as edible and reported in the previous section were collected. The collection period occurred at the end of the rainy season (September and October). The collection process followed the same criteria applied for the biomass and botanical composition sampling; only leaves and young stems up to a height of 1.5 m were sampled. No distinction was made between the vegetation classes where the specimens were found, and likewise, plant age classes were not differentiated. Samples were oven dried at 60 ºC for 48 hours and ground through a 1 mm sieve for laboratory analyses.

Determination of nutritional components

The first part of the determination of the nutritional components of the forage samples was carried out at the laboratory for animal nutrition, Faculty of Veterinary Medicine, UNAM. Each plant species sample was analysed in duplicate. Nitrogen (Kjeldhal method), ash (combustion at 600 C), and fat (extraction by solvents) content (AOAC, 1990). Subsequently, determination of neutral detergent fibre (NDF) contents took place at the laboratory of nutrition, IERM, University of Edinburgh. The modified micro technique for NDF (Pell and Schofield, 1993) was used and also determined in duplicate.

The *in vitro* gas production technique was carried out in duplicate for the 72 samples using the technique described by Menke and Steingass (1988) with the correction for soluble components by Jessop and Herrero (1996) and the correction for bacterial concentration as reported by Nagadi *et al.* (2000). The cumulative gas production (ml) was recorded at 1, 2, 3, 4, 5, 6, 8 hours; then at 4-hour intervals until 60 hours; and thereafter at 72, 84, 96 and 120 hours of incubation. At the end of the incubation period, the residual content was analysed for NDF with the methodology reported by Nagadi *et al.* (2000).

The Marquart algorithm as implemented in GraFit© 3.0 (Erithacus Software Ltd.) was used to fit the cumulative gas volumes to the equation developed by Krishnamoorthy *et al.* (1995):

$$y = B(1 - \exp^{-c(t-lag)}) \tag{5-2}$$

where, y is the cumulative gas production at a given time t (ml); B is the asymptotic gas production from the fermentation of NDF after 120 h (ml); c is the fractional rate of gas production (h^{-1}); and lag is the lag phase before the fermentation of NDF begins (h).

5.5.2 Results

Table 5-7 shows the NDF, NDF digestibility (NDFD), gas production and crude protein ($N \times 6.25$) for the 72 plant species.

Table 5-7 NDF, NDF digestibility, gas production parameters, and crude protein values by plant species

Family	*Name*	NDF (g/kg DM)	NDFD* (%)	*B*	*c*	lag	CP** (g/kg DM)
Anemiaceae	*Anemia* sp.	330.9	14.22	25.8	0.043	4.0	64.7
Apiaceae	*Eryngium* sp.	597.1	51.86	32.6	0.043	3.1	101.1
Aristolochiaceae	*Aristolochia* sp.	314.8	57.81	27.5	0.051	4.0	131.9
Asteraceae	*Archibaccharis* sp.	622.7	19.63	11.8	0.031	3.4	93.4
	Baccharis conferta	363.3	45.72	23.3	0.036	4.6	115.5
	Bidens sp.	326.9	60.19	33.1	0.093	4.4	114.5
	Cirsium jorullense	593.9	52.10	39.0	0.064	4.2	115.8
	Eupatorium areolare	276.9	59.96	32.8	0.034	4.2	76.4
	Gnaphalium sp.	483.8	34.34	22.1	0.041	4.5	237.4
	Melampodium sp.	685.2	23.82	29.0	0.038	4.0	74.8
	Pluchea sp.	348.5	70.61	31.0	0.089	4.4	116.2
	Rumfordia floribunda	283.4	67.76	41.5	0.095	4.8	174.8
	Senecio sp.	401.0	59.45	42.1	0.051	4.1	114.5
	Stevia sp.	426.5	78.00	30.7	0.069	6.8	117.5
	Tagetes erecta	230.6	84.73	30.4	0.135	4.0	113.9
	Taraxacum officinale	486.2	31.96	26.2	0.048	4.7	114.1
Betulaceae	*Alnus* sp.	687.6	31.60	28.5	0.036	4.0	73.9
Buddlejaceae	*Buddleja americana*	307.7	82.65	32.5	0.052	5.6	146.7

Table 5-7 *Continued*

Family	*Name*	NDF (g/kg DM)	NDFD* (%)	*B*	*c*	lag	CP** (g/kg DM)
Buddlejaceae (*cont.*)	*Buddleja cordata*	592.7	68.42	29.7	0.054	3.1	163.6
	Buddleja parviflora	483.5	58.97	25.1	0.052	5.5	144.7
	Buddleja sessiliflora	372.1	70.58	22.4	0.064	3.9	172.8
Caryophyllaceae	*Stellaria ovata*	464.2	29.20	24.6	0.050	4.3	136.9
Cistaceae	*Helianthemum glomeratum*	391.2	39.38	24.5	0.032	3.3	98.7
Commelinaceae	*Commelina coelestis*	450.0	46.26	28.7	0.062	3.2	115.8
	Gibasis sp.	450.0	46.26	28.7	0.062	3.2	111.7
	Tripogandra disgrega	437.9	15.25	14.7	0.049	3.1	152.6
Convolvulaceae	*Ipomoea purga*	447.4	78.66	34.1	0.087	4.6	161.8
Crassulaceae	*Sedum* sp.	331.5	61.90	41.2	0.057	4.1	113.6
Cyperaceae	*Bulbostylis* sp.	296.8	81.80	30.3	0.089	4.2	121.8
	Cyperus sp.	296.8	81.80	30.3	0.089	4.2	127.6
Dryopteridaceae	*Woodsia* sp.	305.0	80.98	34.3	0.067	4.3	64.8
Fabaceae	*Astragalus* sp.	360.0	68.28	38.5	0.084	5.1	76.5
	Cologania biloba	238.8	64.01	21.4	0.034	7.6	85.9
	Desmodium sp.	216.5	37.68	22.6	0.034	3.9	173.4
	Lupinus campestris	466.9	61.99	29.9	0.093	4.3	243.2
	Phaseolus coccineus	394.9	61.80	29.4	0.094	4.1	202.5

Table 5-7 *Continued*

Family	***Name***	**NDF (g/kg DM)**	**NDFD* (%)**	***B***	***c***	**lag**	**CP** (g/kg DM)**
Fabaceae (*cont.*)	*Trifolium amabile*	330.7	74.57	32.2	0.049	4.9	186.8
	Trifolium repens	273.4	82.69	37.1	0.097	4.1	334.7
Fagaceae	*Quercus laurina*	396.6	20.06	22.6	0.019	3.9	125.8
Gentianaceae	*Sabatia* sp.	285.2	69.27	31.5	0.105	4.2	157.2
Geraniaceae	*Erodium cicutarium*	344.2	74.97	36.2	0.110	4.7	109.7
	Geranium albidum	283.9	82.47	35.4	0.059	4.4	166.3
Lamiaceae	*Lepechinia caulescens*	310.0	76.14	38.0	0.069	4.8	144.2
	Salvia lavanduloides	416.7	62.36	27.5	0.068	4.7	151.5
	Scutellaria sp	468.2	57.05	25.6	0.067	4.5	129.4
	Stachys coccinea	358.7	78.58	35.2	0.061	4.1	200.2
Onagraceae	*Fuchsia microphylla*	399.8	34.49	27.9	0.032	3.0	93.4
Orchidaceae	*Malaxis* sp.	357.1	20.76	22.7	0.021	1.7	100.7
Passifloraceae	*Passiflora* sp.	280.8	58.18	29.6	0.091	4.1	118.2
Poaceae	*Bromus carinatus*	700.2	63.53	38.7	0.045	5.2	94.6
	Festuca amplissima	597.9	72.38	36.7	0.082	4.9	64.7
	Muhlenbergia robusta	638.7	85.17	49.4	0.061	4.0	53.1
	Panicum sp.	612.0	77.72	36.4	0.070	4.6	110.9
	Pennisetum clandestinum	827.0	58.60	45.4	0.040	4.6	74.0

Table 5-7 *Continued*

Family	*Name*	NDF (g/kg DM)	NDFD* (%)	*B*	*c*	lag	CP** (g/kg DM)
Poaceae (*cont.*)	*Stipa ichu*	600.0	73.00	51.4	0.047	4.7	84.9
	Vulpia myuros	603.4	73.23	51.4	0.047	4.7	90.9
Pteridaceae	*Cheilanthes arizonica*	258.1	64.65	33.3	0.086	5.5	137.6
	Pellaeae ovata	274.4	79.46	28.3	0.134	4.5	227.6
Ranunculaceae	*Clematis dioica*	261.4	80.38	39.7	0.088	3.9	162.2
	Thalictrum sp.	481.1	51.97	34.8	0.081	4.3	174.6
Rosaceae	*Alchemilla procumbens*	346.7	50.14	25.7	0.034	5.8	139.3
	Crataegus mexicana	355.5	29.78	27.1	0.039	4.0	91.4
	Prunus capulí	447.7	8.96	29.7	0.022	4.2	80.8
	Rubus sp.	557.7	44.61	31.0	0.047	4.4	97.4
Rubiaceae	*Bouvardia ternifolia*	302.8	63.10	29.4	0.108	4.3	169.2
	Crusea coccinea	337.2	56.90	32.0	0.103	4.4	100.5
	Didymaea alsinoides	362.4	59.18	30.4	0.075	4.6	222.4
Salicaceae	*Salix paradoxa*	322.4	59.19	39.5	0.080	4.9	115.7
Scrophulariaceae	*Castilleja tenuiflora*	358.7	38.24	34.5	0.030	3.9	93.3
	Penstemon campanulatus	340.8	64.98	25.2	0.084	3.9	232.8
Solanaceae	*Solanum stoloniferum*	282.5	65.76	29.5	0.093	4.2	123.6
Valerianaceae	*Valeriana urticifolia*	315.4	61.89	31.0	0.075	6.6	154.9

*NDF digestibility; **crude protein

An ANOVA was carried out to determine if there were significant differences between botanical families for the NDF, digestible cell wall (DCW), *B* and crude protein (CP) values. Families with only one species represented within them were not included in the analysis. The results showed that there were significant differences between the means of the families for all four categories of nutritional values ($F = 4.6$, $P < 0.01$; $F = 11.3$, $P < 0.01$; $F = 3.1$, $P < 0.01$; $F = 2.1$, $P < 0.01$respectively).

A post-hoc Tukey test was carried out and its results are shown in Table 5-8. It can be noticed that the Poaceae family had significantly different mean values for all four categories of nutritional components (NDF, DCW, *B* and CP) from at least one of the other families included in the analysis. Only one other pair of families (Buddlejaceae and Rosaceae) differed significantly from each other and only in one category (DCW). In addition, the families that were significantly different in NDF values from the Poaceae family were, with one exception, those families that did not differ significantly in B values.

It should be remembered that plants from the Poaceae family are grasses. The results showed that grasses were the plant species with the highest content of structural carbohydrates (NDF), as well as the ones that showed the highest NDFD values. However, although the Poaceae family stood out with the highest *B* values, it does not differ significantly from the potential supply of fermentable carbohydrates of some other families.

Regarding CP, the Fabaceae family showed the highest values, although they did not differ significantly from other families. Most of grazing ecology principles focus on the fact that fabaceaes (legumes) should be perpetuated within grazing systems to provide high quality fodder. Although this appeared to be the case in the Coajomulco system, the high diversity of plants also provided many other species with considerable CP contents that are not significant different from those of the Fabaceae family.

It can be deduced by the results shown in Table 5-8 that it is not always possible to infer the values of a species' nutrient content from its family because of the high variability of species' values within families. For example, the Asteraceae family showed a high level of variability in its nutritional values. However, the results of this analysis suggest that for the Poaceae and Fabaceae families it is possible to infer the value of a particular plant species from the values shown by that family.

Table 5-8 Tukey test for ANOVA showing the mean values for NDF, digestible cell wall (DCW), *B* and CP across botanical families*

	NDF**		DCW**		B**		CP**	
Family	**Mean**	**s.e.**	**Mean**	**s.e.**	**Mean**	**s.e.**	**Mean**	**s.e.**
Asteraceae	425.3^{a}	39.4	$203.8^{a,c}$	17.2	30.2^{a}	2.3	$121.4^{a,b}$	11.8
Buddlejaceae	$439.0^{a,b}$	62.8	301.9^{c}	35.7	27.4^{a}	2.3	$156.9^{a,b}$	6.8
Commelinaceae	$446.0^{a,b}$	4.0	$161.0^{a,c}$	47.1	24.0^{a}	4.6	$126.7^{a,b}$	13.0
Cyperaceae	296.8^{a}	2.1	$242.8^{a,c}$	3.4	$30.3^{a,b}$	8.0	$124.7^{a,b}$	2.9
Fabaceae	325.9^{a}	33.8	$212.3^{a,c}$	26.7	29.8^{a}	2.8	186.1^{a}	33.7
Geraniaceae	314.0^{a}	30.2	$246.1^{a,c}$	12.0	$35.8^{a,b}$	0.4	$138.0^{a,b}$	28.3
Lamiaceae	388.4^{a}	34.4	$261.2^{a,c}$	9.6	$31.6^{a,b}$	2.0	$156.3^{a,b}$	15.3
Poaceae	654.2^{b}	31.9	466.0^{b}	15.0	44.2^{b}	2.6	81.9^{b}	7.4
Pteridaceae	266.2^{a}	8.1	$192.4^{a,c}$	25.6	$30.8^{a,b}$	2.5	$182.6^{a,b}$	45.0
Ranuculaceae	$371.2^{a,b}$	109.8	$230.1^{a,c}$	19.9	$37.2^{a,b}$	2.5	$168.4^{a,b}$	6.2
Rosaceae	$426.9^{a,b}$	49.2	142.1^{a}	44.8	28.4^{a}	1.2	$102.2^{a,b}$	12.8
Rubiaceae	334.1^{a}	17.3	$199.1^{a,c}$	7.7	$30.6^{a,b}$	0.8	$164.0^{a,b}$	35.3
Scrophulariaceae	$349.8^{a,b}$	9.0	$179.3^{a,c}$	42.1	$29.8^{a,b}$	4.6	$163.0^{a,b}$	69.8

*Families with only one species represented within them from the sampling were not included in the analysis

** Values with the same superscripts are not significantly different at $P < 0.05$

Chapter 6

Spatial Analysis and Modelling of Abiotic and Biotic Factors of Coajomulco's Grazing System

6.1 Introduction

This chapter is concerned with the analysis of the plant-animal interactions that emerged from Coajomulco's grazing systems. The first section presents some theoretical background that was considered for the development of the analysis. Subsequently, the methodological framework and the analysis are presented in two sections. Section 6.4 presents the spatial analysis of the abiotic factors of the grazing systems, whilst in sections 6.5 to 6.7 the biotic factors are addressed through the application of simulation and theoretical models. The ultimate objective of the analysis presented in this chapter is to produce the data that will be used as inputs in the optimisation model that will be presented in Chapter 7.

6.2 Theoretical framework of plant-animal interactions

The interactions between plants and animals are key processes that influence the functioning and sustainability of a grazing system. Such interactions are complex and reflect the spatial and temporal heterogeneity of the system (Senft, 1989; Bailey *et al.*, 1996; Tainton *et al.*, 1996). Laca (2000) emphasizes that two aspects of spatial heterogeneity can be distinguished in plant-animal interaction's components: their variability at the smallest scale and their spatial arrangement.

The concept of different spatial levels of plant-animal interactions was presented by Senft *et al.* (1987). These authors described herbivore foraging as a hierarchical process ranging from landscape to bite scale. In addition, Senft *et al.* (1987) stated that herbivores can select among options at each scale, where each decision constrains the choices at smaller scales of heterogeneity. It is possible to classify the factors that influence the heterogeneity in each hierarchical class as abiotic and biotic. Whilst abiotic factors play a major role at a landscape level, the actual foraging action (forage removal) is mainly affected by biotic factors at smaller scales (Senft *et al.*, 1987; Brock and Owensby, 2000). It has therefore been suggested by some authors (e.g. Loehle and Rittenhouse, 1982; Senft, 1989; Brock and Owensby, 2000) that more practical and effective answers can be derived if the analysis of plant-animal interactions accounts for the influence of landscape-scale abiotic features on smaller scale foraging decisions.

6.2.1 Abiotic factors and grazing distribution patterns

Abiotic factors are considered to be geophysical features that influence the heterogeneity of grazing patterns at a landscape level. A heterogeneous defoliation pattern occurs not only due to variation on composition and production of grazing resources, but also because of the variability of topographic features (Wade *et al.*, 1998). Complex interactions between topographic characteristics and the ecology of plant communities make the isolated identification of these effects difficult. However, several abiotic factors have been identified as important influences on grazing distribution. The most important seems to be slope (Cook, 1966; Senft *et al.*, 1983) and distance from water points (Senft *et al.*, 1983; Owens *et al.*, 1991). The relevance of these factors will depend on the particular environmental and topographic characteristics of each grazing system (ranging from intensively managed paddocks to rangeland grazing in arid regions). Some other abiotic factors have also been identified as capable of affecting grazing patterns: distance to mineral supplement, proximity to fences, abundance of weeds, shade availability, resting points and man-made trails (Senft *et al.*, 1983; Brock and Owensby, 2000; Ganskopp *et al.*, 2000).

Foraging decisions are influenced whether positively or negatively by spatial elements. Thus, it can be assumed that diet selection and nutrient intake are constrained by features acting at the landscape or ecosystem level (Senft *et al.*, 1983; Brock and Owensby, 2000). It is then considered that spatial characteristics of grazing are important for the sustainability and understanding of the environmental impacts of grazing (Laca, 2000).

6.2.2 Biotic factors and foraging strategies

Biotic factors are the characteristics inherent in plant species and animals that determine heterogeneity in forage removal through diet selection and foraging strategies. Morphological and physiological characteristics of both plant communities and grazers can affect the stability and composition of both the ecology of plant communities and diet (Arnold, 1985; Parsons *et al.*, 1991). Thus, understanding the heterogeneity of biotic factors requires, for plants, knowledge about their physiology, vegetation dynamics, adaptation and tolerance under a wide range of grazing pressures (Parsons *et al.*, 1983; Briske, 1996; Gordon, 2000; Soussana and Oliveira-Machado, 2000). On the other hand, for the grazer knowledge is required about intake and selection responses to the state, and relative availability of alternatives within the plant community (Parsons *et al.*, 1991; Spalinger and Hobbs, 1992; Laca and Demment, 1996).

From an agricultural point of view, it could be considered that the most important consequence of the plant-animal interaction is the ability to predict intake. Animal responses to nutrients and managerial issues such as supplementation strategies and estimation of stocking rates are all based on intake prediction (Senft *et al.*, 1987). Following Herrero *et al.* (1998), intake prediction can be achieved through three different approaches. In the first approach, prediction of intake is derived from systems of energy requirements such as NRC (1985) for sheep. The second approach establishes relationships between herbage mass and intake (e.g. Finalyson *et al.*, 1995; Armstrong *et al.*, 1997b). Finally, the third approach measures grazing behaviour according to a basic form in which bite size is multiplied by biting rate by grazing time (Hodgson *et al.*, 1994).

Diet selection as an expression of the plant-animal interaction.

Based on Thornley *et al.* (1994) and Laca and Demment (1996), the approaches to the understanding and prediction of diet selection can be divided in three: i) empirical, ii) mechanistic and iii) goal-orientated. In the empirical approach "selectivity coefficients" are assigned according to physical and chemical characteristics of plant species (e.g. Kibon and Orskov, 1993). The mechanistic approach studies the processes that determine intake behaviour at fine and complex levels of resolution (e.g. Parsons *et al.*, 1994). Finally, the goal-orientated approach is related to the optimal foraging theory (see below).

The optimal foraging theory establishes that decision rules are taken by grazers when foraging (Belovsky, 1986; Stephens and Krebs, 1986; Illius and Gordon, 1993). Stephens and Krebs (1986) distinguished three main views about the nature of foraging decisions. According to the nutrient intake maximisation view, grazers select plant species that maximise the rate of energy intake (Illius and Gordon, 1993; Laca and Demment, 1996). In the second view (nutrient selection intake), herbivores select diet components to complement nutrient intake (Rapport, 1981). Finally, the third view suggests that plant toxins determine diet selection (Bryant *et al.*, 1989; Freeland and Saladin, 1989).

Van Wieren (1996) suggested that the nutrient complementary theory was more frequently implied than tested. This author also argued that the view about the role of plant toxins affecting diet selection could be explained by the energy maximisation theory. This was supported by Provenza (1995), who highlighted that allelochemicals or other plant toxins reduced the digestive benefits of a plant. Thus, digestion inhibition and low nutritive value may influence the grazer to select other more attractive plant species (Launchbaugh, 1996).

Although the energy maximisation theory is the one that has been the focus of much scientific research, Bergman *et al.* (2001) suggested that animals can exert combined strategies. They highlighted that habitat complexity and heterogeneity of resource abundance in time and space implied that foraging strategies may not be constant, but may also vary through time and space. In addition, van Wieren (1996) suggested that herbivores can produce "imperfect" foraging decisions as a response to the constantly changing environment.

6.3 Methodological framework for the hierarchical analysis of plant-animal interactions in Coajomulco

The analysis of the plant-animal interactions was carried out considering the grazing system as a hierarchical process (Senft *et al.*, 1987; Bailey *et al.*, 1996). Following Brock and Owensby (2000) and Laca (2000), multiple scales of heterogeneity can be distinguished in the grazing process, each scale constraining the choices at a smaller one. Two hierarchical levels were considered in this study: the landscape level and the plant community level. Figure 6-1 shows the methodological framework for these considerations. Thus, it was assumed that the abiotic factors at landscape level determined the spatial pattern of the grazing distribution. The forage resources were contained in plant communities associated with grazing patches. Thus, the grazing distribution pattern represented the sequence at which each grazing patch was defoliated. The biotic characteristics of each plant community determined the diet selection and biomass intake in each grazing patch. In this way, the grazing process was initially constrained by the physical characteristics of the terrain and subsequently by the plant species characteristics of each grazing patch.

As mentioned before, the main objective of this analysis was to produce input data for the spatial optimisation model. The time scale for field work measurements did not allow either development of validation studies or testing of the conclusions that were drawn from them. Thus, no quantitative predictions can be derived from them at this stage. However, it was felt that the theoretical considerations that were taken into account during the development of this methodology provided the means for the exploratory analysis of Coajomulco's grazing systems. In addition, it was considered that such an approach provided satisfactory objectivity for the level of detail at which the spatial optimisation of next chapter was developed. Some of the assumptions made throughout the analysis can be regarded as "expert knowledge", since they are derived from the understanding of Coajomulco's sheep farming system either from personal experience or interaction with farmers and shepherds. Although no formal participatory exercise was carried out for these purposes, this sharing of knowledge derived from the participatory methodologies is described in previous chapters. Thus, the term "expert knowledge" will be used during the description of this analysis when the information utilised was derived in such a form.

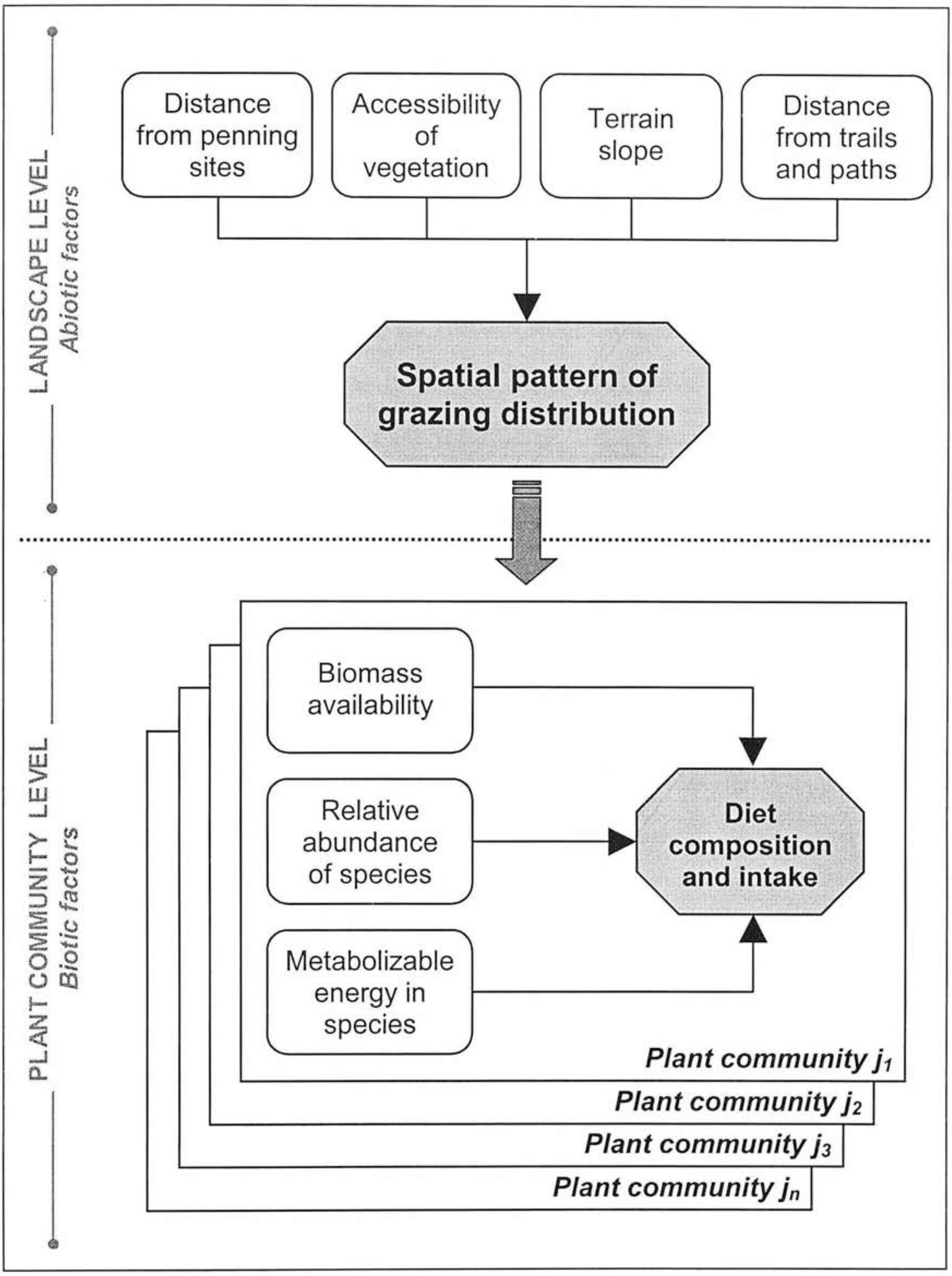


Figure 6-1 Methodological framework for the hierarchical analysis of the plant-animal interactions of the sheep grazing system in Coajomulco

6.4 Spatial analysis of abiotic factors

6.4.1 Methodology

Four abiotic factors were considered for this analysis: i) distance from penning sites, ii) accessibility to vegetation, iii) terrain slope and iv) distance from trails and paths (Figure 6-1). Terrain slope and distribution of trails and paths have been reported as having a major influence in the definition of grazing distribution patterns (see Senft *et al.*, 1983; Owens *et al.*, 1991; Wade *et al.*, 1998). Expert knowledge helped to identify that when sheep flocks were herded, shepherds preferred to travel across wood-clear areas (G&S class) for the sake of comfort. Distance from penning site was regarded as the main influencing factor in the distribution of grazing patterns. As was mentioned in Chapter 3, flocks returned every evening to their penning site situated in the farmers' plots. This feature of the management of the system constrained the extent of the grazing area.

The spatial analysis of the interaction of these four factors was carried out in ArcGIS© 8.1 (ESRI). Three different layers were created to represent the terrain slope, accessibility of vegetation and distance from trails and paths over the grazing zones of Coajomulco. The available grazing area that was produced in Chapter 3 (Section 3.4.3) was used in the spatial analysis. The analysis was carried out with a cell size of 10 × 10 m for all layers (pixel covering 100 m^2).

Terrain slope layer

Digital elevation model (DEM) data at 1 : 50,000 scale covering the whole of Coajomulco were acquired from INEGI (Figure 6-2). The slope was calculated from the DEM and expressed in percent according to:

$$s = \frac{|e_2 - e_1|}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \times 100 \qquad (6\text{-}1)$$

where, *S* was the percent slope; e_1 and e_2 were the elevations of points 1 and 2, respectively; and x_1, y_1 and x_2, y_2 were the respective coordinates of points 1 and 2, respectively.

The slope values were divided into 10 classes with break values of 1, 3, 5, 10, 15, 20, 25, 50 and 100 percent.

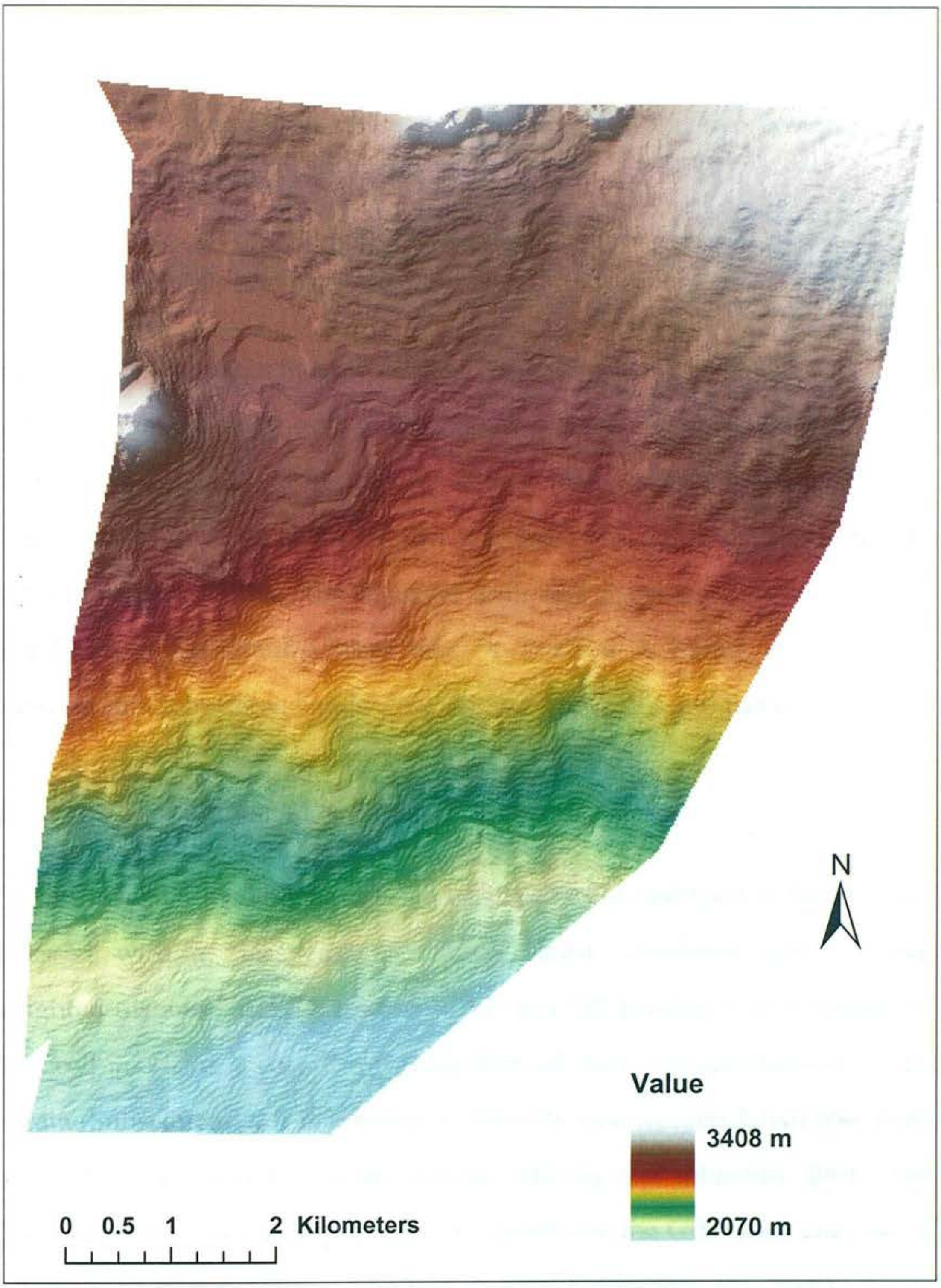


Figure 6-2 Digital elevation model (DEM) for Coajomulco

Accessibility of vegetation layer

The land class cover produced in Chapter 4 (Figure 4-2) was used in this procedure. The vegetation classes were reclassified into two groups: forest areas and wood-cleared areas (G&S class).

Distance from trails and paths layer

All the trails and paths that ran across Coajomulco were identified during the sampling methodology and participatory exercise described in Chapter 3 (sections 3.4.3 and 3.4.4). Expert knowledge coincided with literature reports (Ganskopp *et al.*, 2000) about the fact that there was higher grazing intensity in areas closer to paths. The digitised trails and paths used by shepherd to travel across Coajomulco were used to perform a buffer analysis. One hundred-meter buffered bands were created from trails and paths.

"Cost layer" for grazing pattern distribution

The influence of the abiotic features on the grazing distribution pattern was assessed with a "least-cost movement" layer calculated with a "cost weighted distance" (CWD) routine. CWD is a GIS procedure that assigns to each cell in a layer a cost of travelling derived from physical features of the terrain. Subsequently, it is possible to find the least accumulative cost from each cell to the nearest, cheaper source (McCoy and Johnston, 2001). The CWD procedure has been proved to be useful for the GIS-based analysis of grazing distribution patterns (Wade *et al.*, 1998; Ganskopp *et al.*, 2000).

The CWD routine requires the creation of a new layer that contains the relative cost of travelling through every cell from a given origin (in this case the agricultural areas where the penning sites are located). In order to produce a travel cost layer, the values of the terrain slope, accessibility of vegetation and distance from trails and paths layers were reclassified in a new abstract scale. The ten classes of percent slope were given a value of 1 to 10 from the least steep to the steepest cells respectively. For the vegetation class, the G&S class was assigned with a value of 1, whilst all the woodland classes were assigned a value of 5. Finally, the nearest 100-m buffer ring to the agricultural area was valued as 1, the second nearest as 2, and so on until the farthest ring. This new abstract scale represented the relative preference of flocks and shepherds in travelling over the terrain. Low values in the scale represented greater ease of travelling. The travel cost layer was then calculated:

$$\text{travel cost} = \text{slope} \times \text{vegetation} \times \text{distance} \qquad (6\text{-}2)$$

where, *slope, vegetation* and *distance* are the reclassified values in the new scale for the layers for terrain slope, accessibility of vegetation and distance from trails and paths, respectively. Finally, the CWD procedure was applied using the location of the agricultural land as the origin in the input of the analysis.

6.4.2 Results

Figure 6-3 shows the terrain slope layer and the division of slope values in 10 classes. Figure 6-4 illustrates the procedure for creating the travelling cost layer. The CWD function produced an output layer in which each cell was assigned a value that was the least accumulative cost of travelling from the "entrance" to the grazing area adjacent to the agricultural land (penning sites) Figure 6-5.

It is important to recall that the values associated with this layer do not have units, and simply represent "effortlessness" when sheep flocks travel from their penning sites to the grazing areas. The spatial pattern of Figure 6-5 can be interpreted as the sequence of defoliation that sheep flock follow according to the abiotic factors of the system that determined the ease of movement over the terrain.

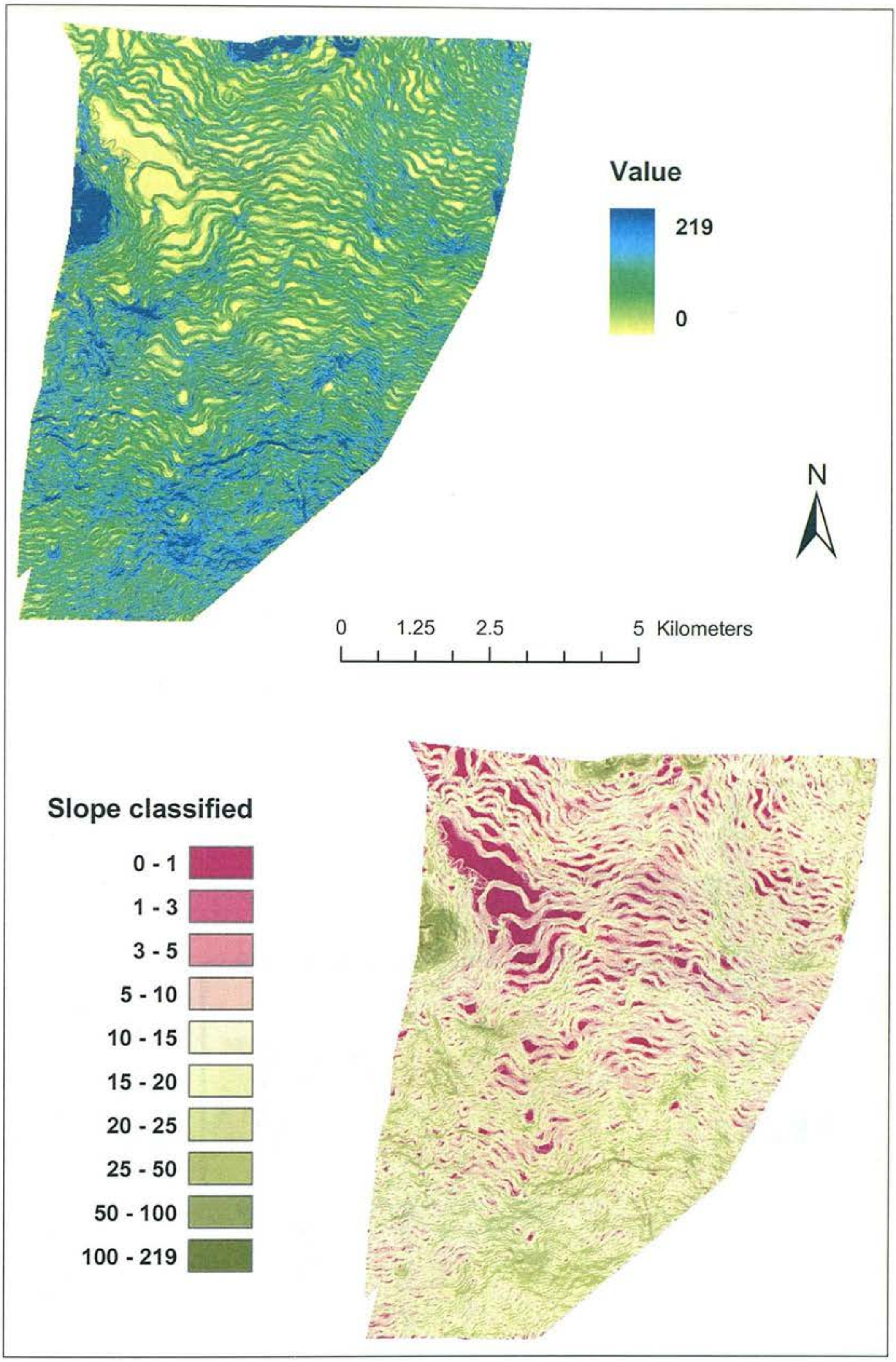


Figure 6-3 Percent slopes and their classification in Coajomulco derived from the digital elevation model

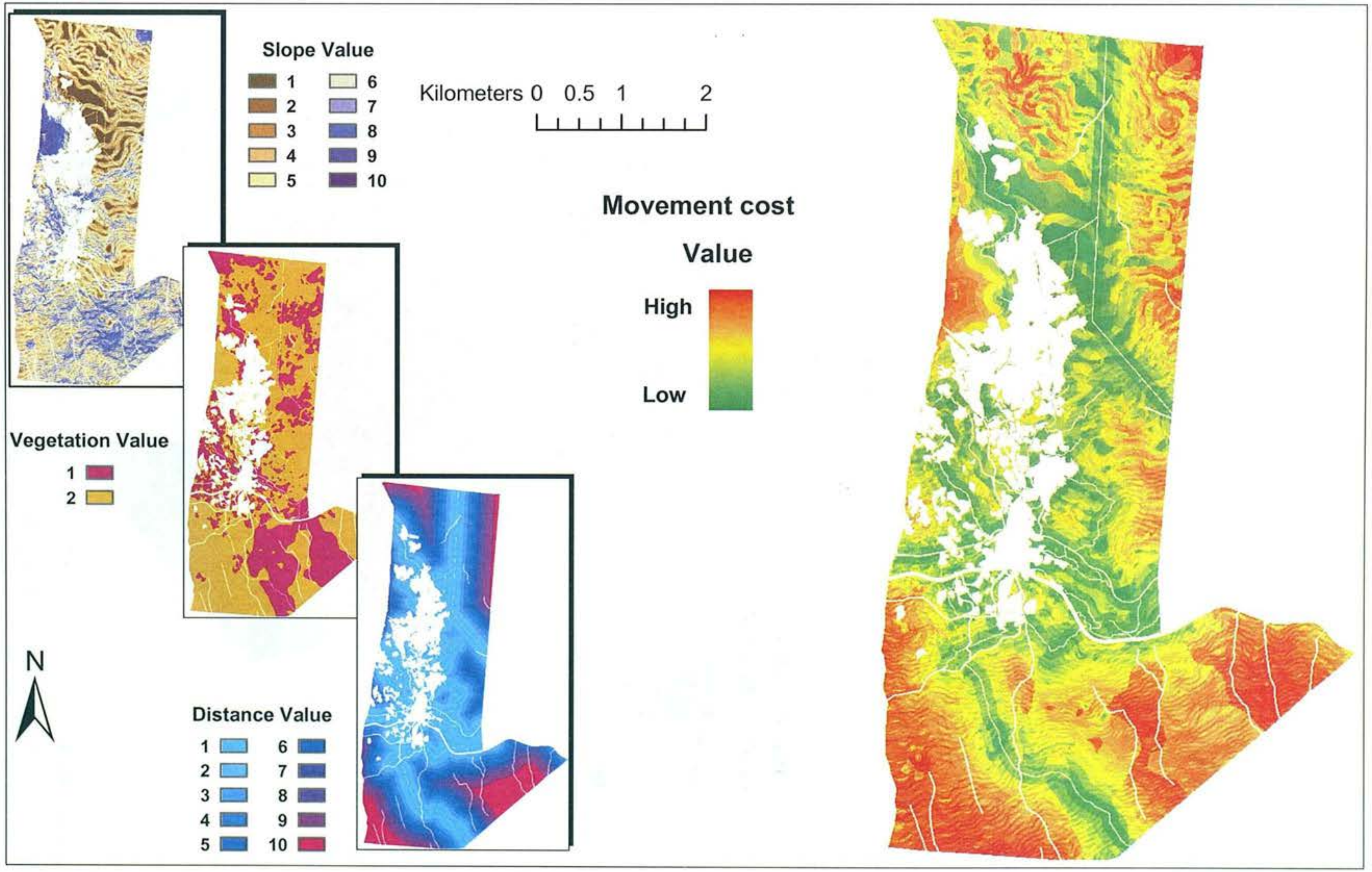


Figure 6-4 Travelling cost layer produced with the reclassified layers for slope, vegetation class and distance from the agricultural area

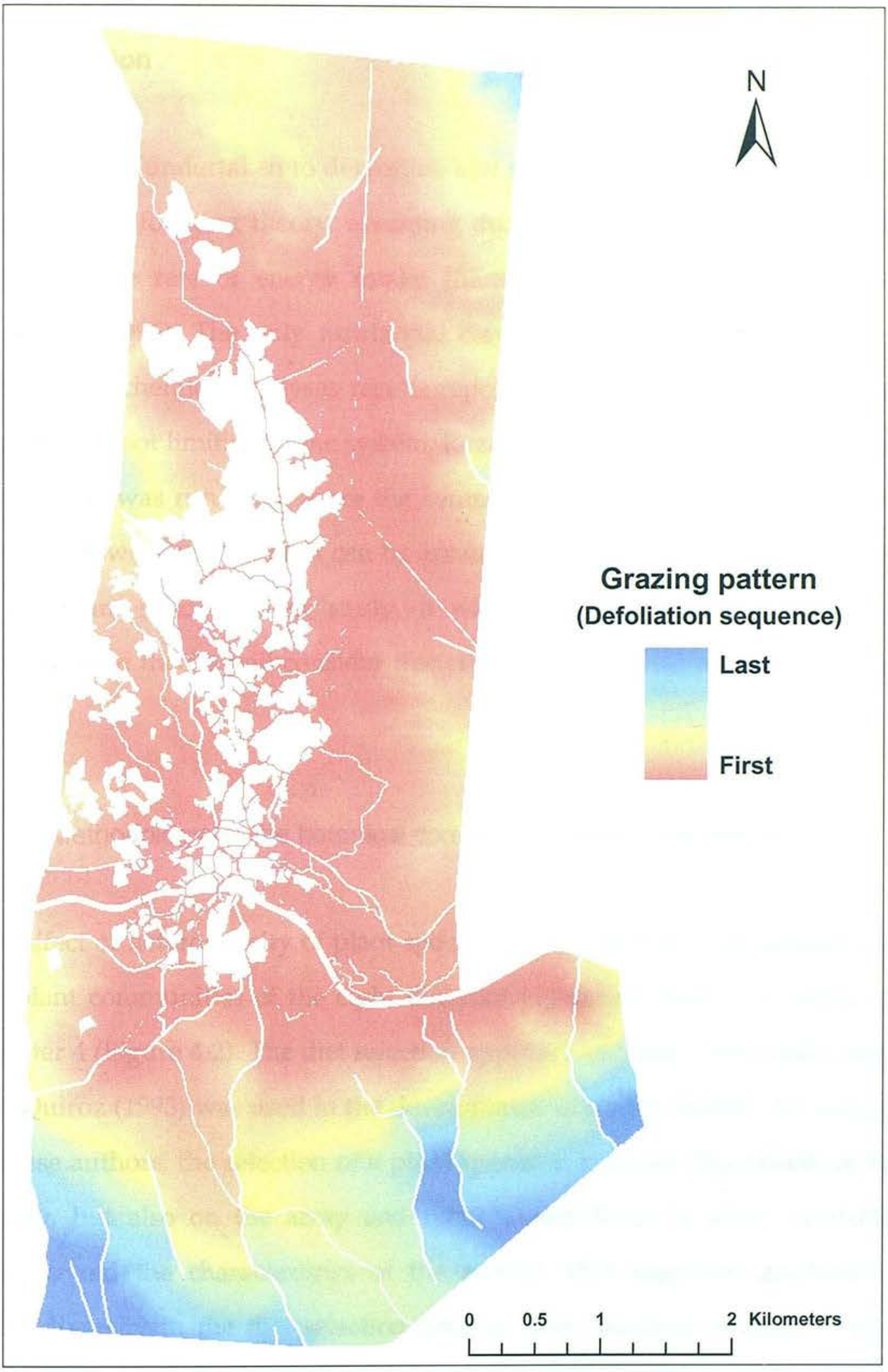


Figure 6-5 Grazing distribution pattern in Coajomulco as obtained by the Cost Weighted Distance procedure

6.5 Modeling of biotic factors at the plant community level. Diet selection

The approach undertaken to determine diet selection followed Stephens and Krebs' (1986) foraging theory, assuming that sheep select plant species that maximise the rate of energy intake (Illius and Gordon, 1993; Laca and Demment, 1996). The only nutritional component considered was energy because the chemical analyses results reported in Chapter 5 suggested that protein was not limiting in the system. Regarding the content of plant toxins, no analysis was run to measure the content of any allelochemicals in plant species. However although it can be assumed that they were indeed present in the plant species under study, it was also assumed that the energy maximisation theory will consider this effect, as mentioned above in Section 6.2.2.

6.5.1 Methodology for the botanical composition of the selected diet

The effect of heterogeneity of plant species in diet selection was assessed for the plant communities of the eight different vegetation classes identified in Chapter 4 (Figure 4-2). The diet selection approach of Stuth (1991) and Genin and Quiroz (1993) was used in the development of a static model. According to these authors, the selection of a plant species is not only dependant on its quality, but also on the array and relative abundance of other available species, and the characteristics of the animal. This approach emphasises plant diversity in the diet selection process, and considers a single forage species the fundamental unit. Genin and Quiroz (1993) introduced the concept of potential alimentary capacity (PAC) of a plant species to hypothetically explain its contribution to the diet selected by a grazing animal. PAC is calculated as a function of both the plant species' quality and relative abundance within the community. A modified definition of PAC was used for this study, which was calculated as:

$$\mathrm{PAC}_{ij} = R_{ij}^{\frac{1}{S_j}} \times Q_i^{S_j} \times 1000 \qquad (6\text{-}3)$$

where PAC_{ij} was the potential alimentary capacity for plant species i in plant community (grazing patch) j; R_{ij} was the probability of encountering species i in community j; S_j was the selectivity index of the animal in community j; and Q_i was the quality index of species i.

Probability of encountering species (R_{ij})

In each grazing patch j, the probability of finding the plant species i corresponded to the relative abundance of i in the plant community j. R_{ij} is then obtained from the botanical composition data reported in Chapter 4 (Section 4.4).

Selectivity index of sheep (S_j)

The selectivity index was included in the computation of PAC, hypothesising that the maximisation of energy intake was a function of the animal's energy requirements and that it was concurrently influenced by the relative quality of the species contained in the plant community j (Genin and Quiroz, 1993; Bailey *et al.*, 1996; Laca, 2000). The selectivity index of sheep was calculated:

$$S_j = \frac{\text{ME requirements of sheep}}{\text{ME content of plant community } j} \qquad (6\text{-}4)$$

where, ME was the metabolizable energy expressed in MJ/kg dry matter.

Both ME requirements by sheep and supply in the plant community were calculated through the use of a simulation model (DYNAFEED) for predicting potential forage intake, digestion and animal performance (Herrero *et al.*, 2002). The applicability of an earlier version of this model (Herrero, 1997) in Mexican sheep farming systems has been previously tested with good results (González-Estrada *et al.*, 2000). This model was largely derived from the work of Illius and Gordon (1991, 1992), Sniffen *et al.* (1992) and AFRC (1993). DYNAFEED is divided into two functional sections:

(i) A nutrient supply section, which describes the flow, digestion and fermentation of degraded feed fractions from which intake, digestibility and nutrient supply are estimated.

(ii) A nutrient requirements section, which estimates potential nutrient requirements of the animal, mainly on the basis of AFRC (1993).

According to Herrero *et al.* (2002) this approach represents a major step from the conventional systems of nutrient requirements (e.g. NRC, 1985; INRA, 1989; AFRC, 1993), since DYNAFEED derives them from a dynamic simulation of intake and nutrient supply.

The nutritional values for the plant species reported in Chapter 5 (Section 5.5.2) were used as inputs for DYNAFEED. Simulations were run for a non-pregnant, non-lactating 50-kg ewe.

Quality index of species (Q_i)

Several methods for ranking forage species according to their physical and chemical characteristics have been devised. For this study an index that included the digestibility of NDF in conjunction with CP values adopted from Blackburn and Kothmann (1991) was used. This index was chosen due to its ability to emphasize the sensitivity of diet selection due to the plant species quality. The quality index Q_i was thus calculated:

$$Q_i = \frac{M_i}{\sum M_i} \qquad (6\text{-}5)$$

where,

$$M_i = (1.67 \times (\mathrm{NDFD}_i - 0.20))^2 \times (3.509 \times (\mathrm{CP}_i - 0.015))^2 \qquad (6\text{-}6)$$

NDFD_i was the digestibility of the NDF of the plant species *i*; and CP_i was the crude protein content of *i*.

Contribution of plant species to the selected diet

Once the PAC for each species in each plant community was calculated, the theoretical botanical composition of the diet was calculated as defined by Genin and Quiroz (1993):

$$\mathrm{TCD}_{ij} = \frac{\mathrm{PAC}_{ij}}{\sum_i \mathrm{PAC}_{ij}} \qquad (6\text{-}7)$$

where, TCD_{ij} was the theoretical contribution of species *i* to the diet selected in the plant community *j*.

6.5.2 Results for diet selection

Selectivity index of sheep (S_j)

Herrero *et al.*'s (2002) DYNAFEED model estimated an average ME requirement for a non-pregnant non-lactating 50-kg ewe of 9.8 MJ/day. Table 6-1 shows the predicted supply of ME in each plant community as well as the calculated selectivity index.

Table 6-1 Predicted metabolizable energy by DYNAFEED and calculated selectivity index of sheep S_j by plant community

Plant community	ME Supply (MJ/kg DM)	S_j
Woodland class A	8.2	0.78
Woodland class B	8.7	0.74
Woodland class C	8.6	0.75
Woodland class D	9.2	0.70
Woodland class E	8.8	0.73
Woodland class F	8.7	0.74
Woodland class G	8.2	0.78
Grass and Scrub class	7.4	0.87

The S_j values suggest that the combination of species in each community provides a sufficient supply of ME. As can be inferred, $S_j > 1$ would indicate plant communities with low potential to meet the animal energy requirements. The selectivity index S_j was specific for each plant community. The role that S_j plays in equation (6-3) influences both the importance given to the relative abundance of each species (R_{ij}) and the quality index of a forage (Q_i). The importance of R_{ij} for determining PAC will inversely depend on the accuracy of the animal to seek plants with the highest nutritional quality (Genin and Quiroz, 1993). On the other hand, S_j is used as an exponent of Q_i because it is assumed that the animal tries to maximise nutrient intake depending on the balance between its nutritional needs and the overall quality of the patch where it is grazing (Senft, 1989; van Wieren, 1996). In nutritionally poor communities ($S_j > 1$), the animal would be forced to look for the best quality species, which is reflected in the PAC ($Q_i^{S_j}$).

Quality index of species (Q_i) and potential alimentary capacity (PAC)

Equation (6-5) produced Q_i values that ranged from 1.4×10^{-7} to 1.38. In addition, PAC_{ij} values obtained with Equation (6-3) ranged from 5.9×10^{-7} to 8.15. Figure 6-6 shows the different values of PAC_{ij}, R_{ij} and Q_i obtained for one plant species that was recorded in all the plant communities, and two more in all except one. It should be remembered that Q_i was constant across plant communities. It can be noticed that PAC_{ij} changes are highly influenced by the relative abundance of the plant species R_{ij}. However, small changes in R_{ij} had a major effect on PAC_{ij} when Q_i is higher. This can be seen by the influence of different Q_i values on the range of PAC_{ij} values of two scarce species, *Trifolium repens* and *Buddleja sessiliflora* (Q_i = 0.162 and 0.026 respectively) in Figure 6-6. The function of PAC_{ij} is that if a plant species has a very high nutritional quality but it is rare in the plant community, its PAC_{ij} will be low (Genin and Quiroz, 1993).

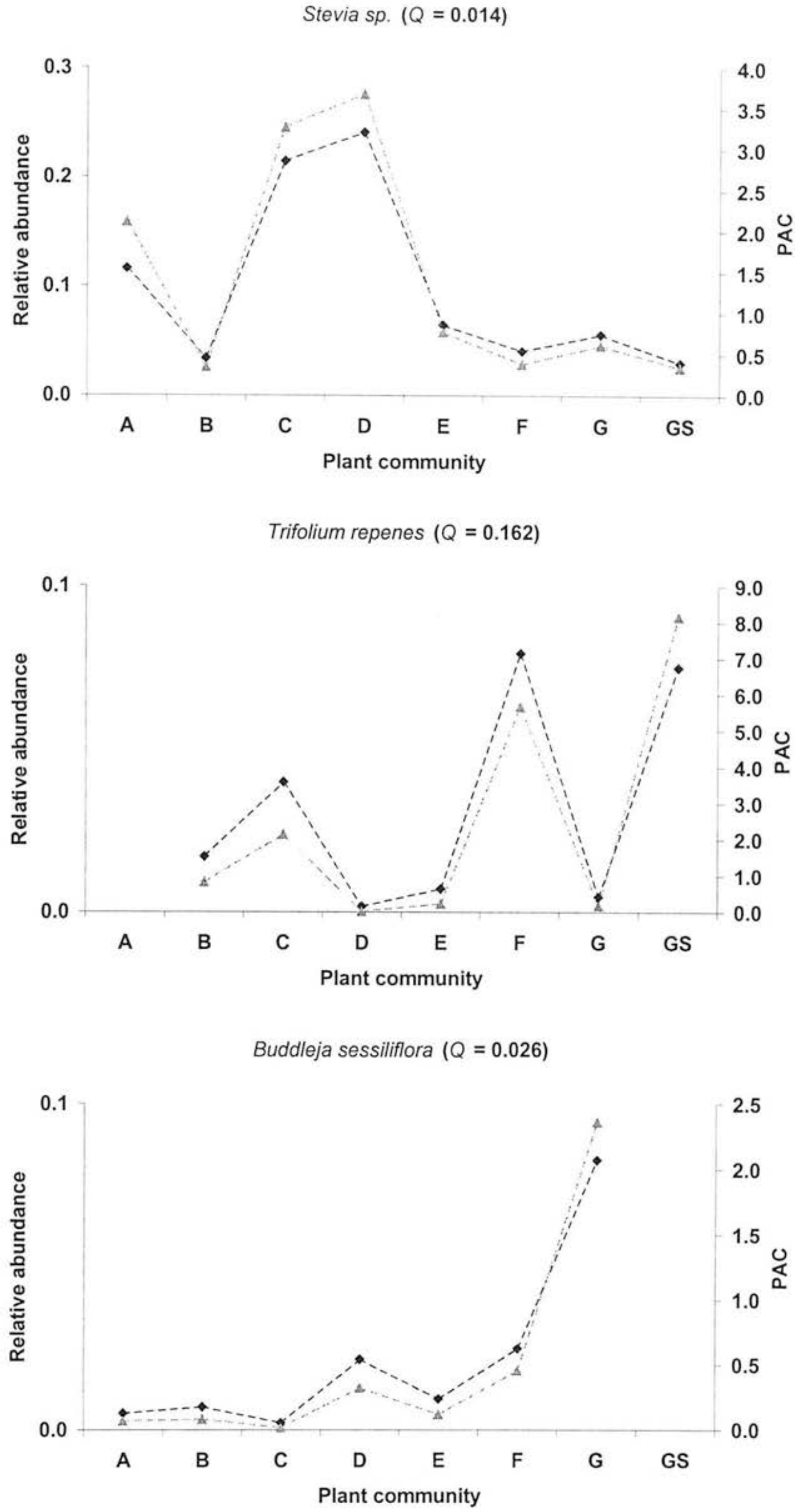


Figure 6-6 Relative abundance (R_i) expressed as proportion (◆), and the potential alimentary capacity (PAC) (▲) of three plant species across plant communities

Theoretical contribution of species to the diet selected (TCD)

The theoretical botanical composition of the selected diet by sheep in each plant community was obtained from Equation (6-7). TCD_{ij} was a function of the abundance and quality of plant species, as well as the relative selectivity of sheep. Thus, it was expected that the diet estimated using TCD_{ij} would be botanically different and nutritionally higher than that which was available in the plant community. Such a difference would reflect the selectivity of sheep in trying to maximise nutrient intake.

Figure 6-7 shows the difference between the botanical composition of plant communities and the hypothetical selected diet. Herrero *et al.*'s (2002) model was used to predict the potential supply of ME by the selected diet. Table 6-2 shows these results indicating the difference with the potential ME supply of the plant community calculated in Section 6.5.1 when calculating S_j.

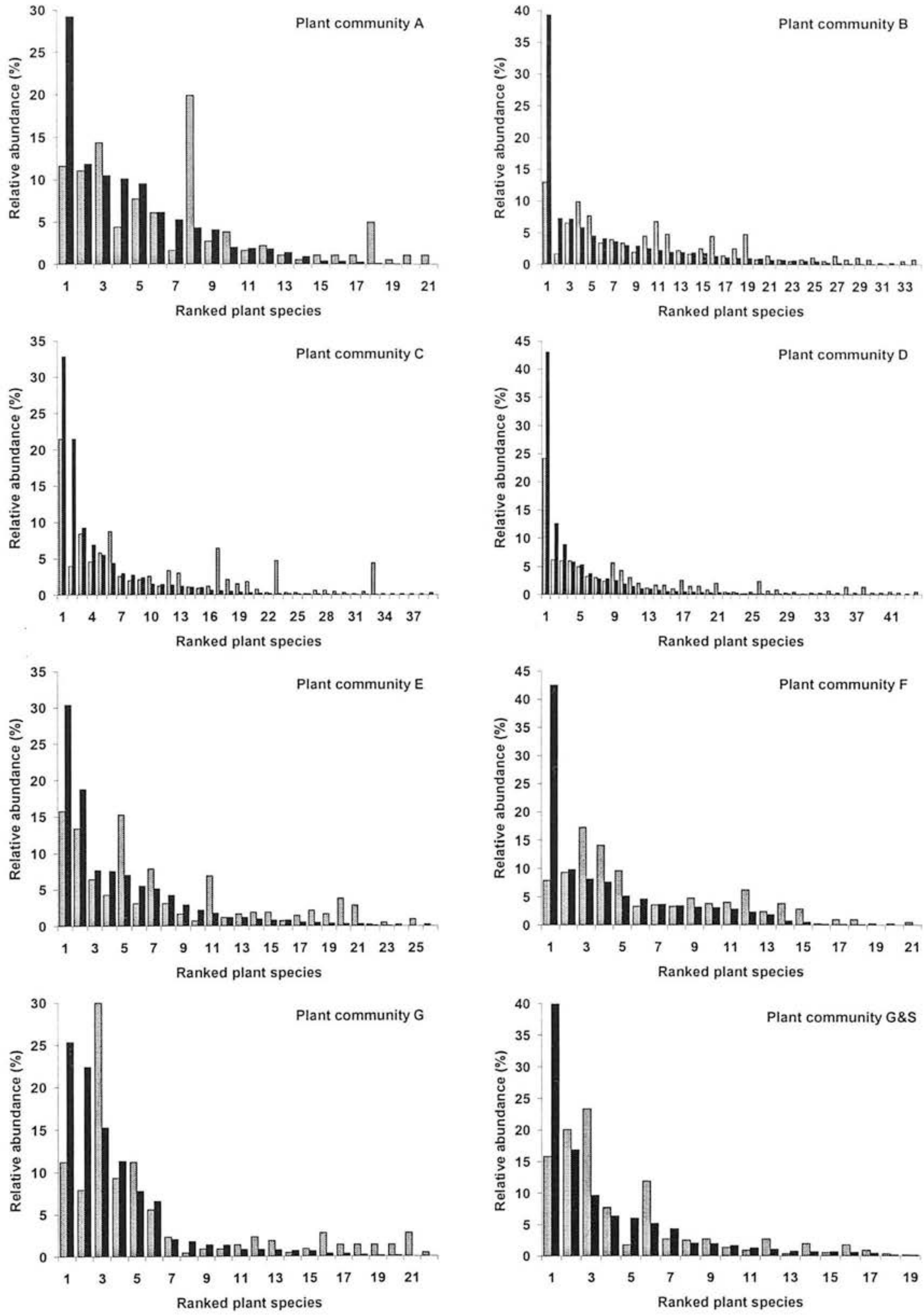


Figure 6-7 Botanical composition of the theoretical selected diet (■), and the edible species in the grazing patch (■). Plant species on the x-axis are ranked according to their relative abundance in the theoretical selected diet.

Table 6-2 Predicted metabolizable energy by DYNAFEED and its relative change for the hypothetical selected diet by plant community

Plant community	ME Supply (MJ/kg DM)	*Change** *(%)*
Woodland class A	9.3	+ 13.4
Woodland class B	9.5	+ 9.2
Woodland class C	9.6	+ 11.6
Woodland class D	9.6	+ 4.3
Woodland class E	9.0	+ 2.3
Woodland class F	9.6	+ 10.3
Woodland class G	9.2	+ 12.2
Grass and Scrub class	9.7	+ 31.1

*Change in relation with the ME supply predicted by the model for all the edible species within each plant community as reported in Table 6-1

6.6 Modelling of biotic factors at the plant community level: biomass availability

6.6.1 Methodology

Biomass availability has been recognised to influence intake, and several models have been developed to explain this effect (e.g. Sibbald *et al.*, 1979; Johnson and Parsons, 1985; Blackburn and Kothmann, 1991; Finalyson *et al.*, 1995). The ultimate applicability of the predictions that can be drawn from these models is the estimation of the constraint that limited biomass availability exerts on the animal's potential intake. This is done by multiplying an estimated relative intake factor by the potential intake.

The effect of biomass availability on the relative intake was assessed with Johnson and Parsons' (1985) model modified by Herrero *et al.* (1998) to include the proportion of leaf in the plant species. This consideration was important due to the methodology applied during the biomass production sampling. As can be recalled from Chapter 5 (Section 5.2.1), only leaves and young stems were collected, and therefore the biomass production data reported in Tables 5-5 can be regarded as totally edible plant material. Following Herrero *et al.* (1998), the relative intake (RI) was calculated:

$$RI = \left(\frac{imax \times \left({LAI}/{K} \right)^{D}}{1 + \left({LAI}/{K} \right)^{D}} \right) \times imax^{-1} \qquad (6\text{-}8)$$

where, imax was the potential intake (kg day^{-1}/animal); LAI was the leaf area index associated to the herbage dry matter; K was the half-maximal response of LAI (calculated as 0.229 × (body weight)$^{0.36}$, according to Herrero *et al.* (2000)); and *D* was a herbage-associated constant.

This model was used as a generalist model, since no data for calibration of plant species were available. It was applied to each plant community as a whole, and no individual distinction for plant species was made. Although it is used in a coarse approach, this model was included in this study in order not to overestimate intake in some plant communities, especially since biomass production across vegetation classes is highly variable. Although the parameters for the functioning of this model were derived from grassland swards, Mnene *et al.*, (1996) provided some evidence that in forb and shrub vegetation the relationship between biomass and intake is similar to the one that prevails in grasslands.

6.6.2 Results

The general function derived from Equation (6-8) is shown in Figure 6-8. According to the edible biomass production results shown in Chapter 5 (Table 5-5), relative intake factors of 0.98, 0.99, 0.84, 0.98, 0.99, 0.97, 1.00 and 1.00, should be used in vegetation classes A to G, and G&S respectively.

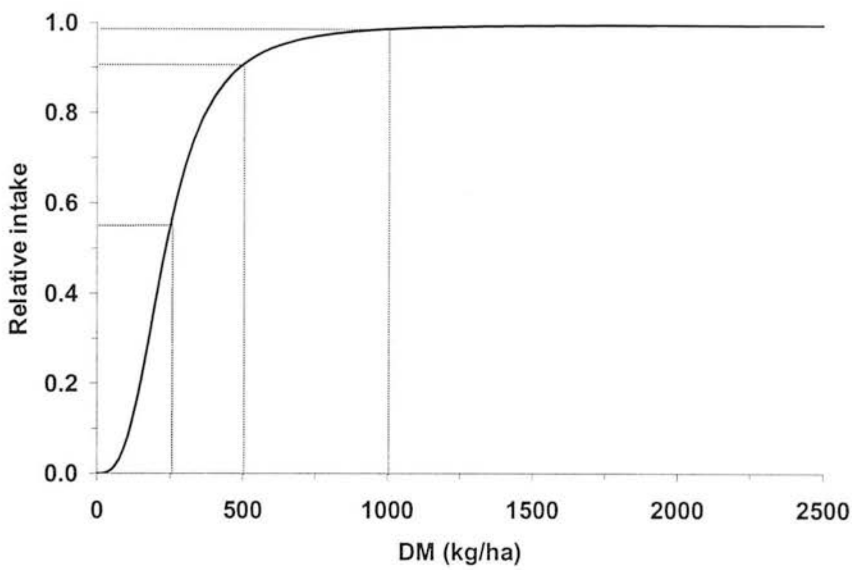


Figure 6-8 Relationship between biomass availability and relative intake as produced by Equation 6-8

6.7 Modelling of biotic factors at the plant community level: flock dynamics

In the last section of this chapter, the exploration of the plant-animal interactions at a plant community level will look at the heterogeneity of the nutritional requirements of sheep and its articulation at flock level. Population dynamics and changes in the physiological status of animals are reflected in the way plant communities are utilised. As highlighted by Stuth and Maraschin (2000), the productivity and ecology of a given grazing environment are strongly influenced by the degree to which animal species match the vegetation composition. A simulation model to represent flock dynamics in Coajomulco was developed to address these issues.

6.7.1 Methodology

A descriptive and dynamic simulation model was developed in order to assess the changes in energy demanded by sheep flocks throughout the grazing season. This model aimed to calculate the ME requirements by flock based on the number of sheep and their physiological status, along with the evolution of the population. It ran on a weekly basis during the 35 weeks of the grazing season (May to December). The model was developed using Stella® 7.02 (High Performance Systems, Inc.).

The ewe and lamb populations were modelled independently, the former being at the core of the model and linking to the latter at the lambing season. Rams were also included. The model was conformed by three two-dimensional arrays of the form:

$$\mathrm{EWE}(s,f) \tag{6-9}$$

$$\mathrm{LAMB}(g,f) \tag{6-10}$$

$$\mathrm{RAM}(f) \tag{6-11}$$

Where, EWE, LAMB and RAM were the arrays for the ewe, lamb and ram population respectively; s and g were the arrays' dimensions for the physiological classes comprised in the ewe and lamb populations respectively; and f was the arrays' dimension that represented the flock. The maximum value of s (s_{max}) was set to five, representing the following physiological classes: reproductive, non-pregnancy, early pregnancy, late pregnancy and lactation. Distinction between single and twin pregnancy and lactation was made. g_{max} was set to nine to represent weaned lambs, and eight classes of growing lambs, from 15 to 50 kg with a step value of 5 kg were given. No distinction of classes was made for rams. Figure 6-9 shows a conceptual diagram of the model.

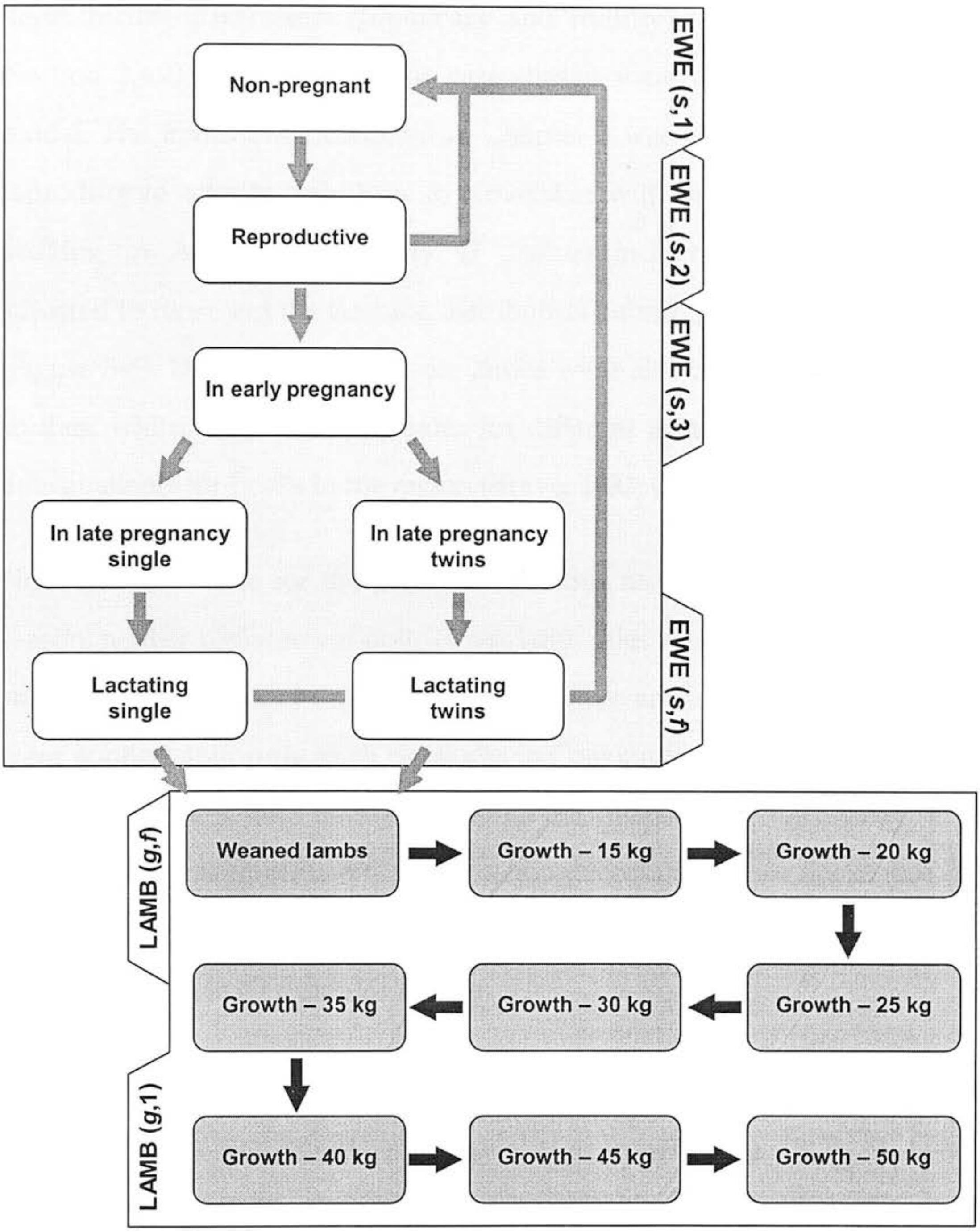


Figure 6-9 Conceptual flow diagram of the flock dynamics model with the array structure for the ewe and lamb populations

Reproductive parameters (prolificacy and fertility) reported in Chapter 3 (Section 3.4.2) obtained from the case studies were used as inputs for the model. The information collected in Chapter 3 was also used to model the reproductive activity from June to November with the incidence of oestrus peaking in August. Seasonality of oestrus incidence and fertility was adjusted to represent the lambing distribution pattern presented in Chapter 3 (Figure 3-5). Daily weight gains for lambs were also obtained from the case studies, whilst lamb mortality rates for different ages were estimated from data available for flocks in the region (Bravo, 1993; CEIEPO, 1995).

Since the time scale for the predictions of this model was set for the rainy season, neither replacement policies nor lamb sales were included. The array-structure of the model implied that productive and reproductive variables were applied uniformly to all the flocks in Coajomulco. However, it was also possible to handle each flock's individual information when necessary. This, for instance, was important for representing accurately those flocks that did not include breeding stock but only lambs that were bought before the lambing season in Coajomulco started.

The ME requirements for each class within the ewe and lamb populations and for the ram population were calculated as described by the AFRC (1993) nutrient requirement system. ME requirements for maintenance, early pregnancy, single and twin late pregnancy, single and twin late lactation and weight gain were considered.

6.7.2 Results

The output of the model represented the dynamics of each of the 38 flocks and produced on a weekly basis the changes in head numbers and ME requirements. Figure 6-10 shows the distribution of the whole ewe and lamb population for Coajomulco throughout the grazing season. Figure 6-11 illustrates the changes in ME requirements as the grazing season progresses in ten flocks of different size.

It can be noticed that the peak in the global demand of ME did not take place during the grazing season. The main reason for this can be attributed to the late start of the reproductive season due to low feed availability during the dry season (Galina *et* al., 1996). The development of this model represented an important tool for the exploration of different managerial regimes that could improve the matching of supply and demand of forage, particularly concerned with reproductive manipulation and feeding strategies. However, this was outside the scope of the current study. The results derived from this model were used as the main input in the optimisation model described in next chapter.

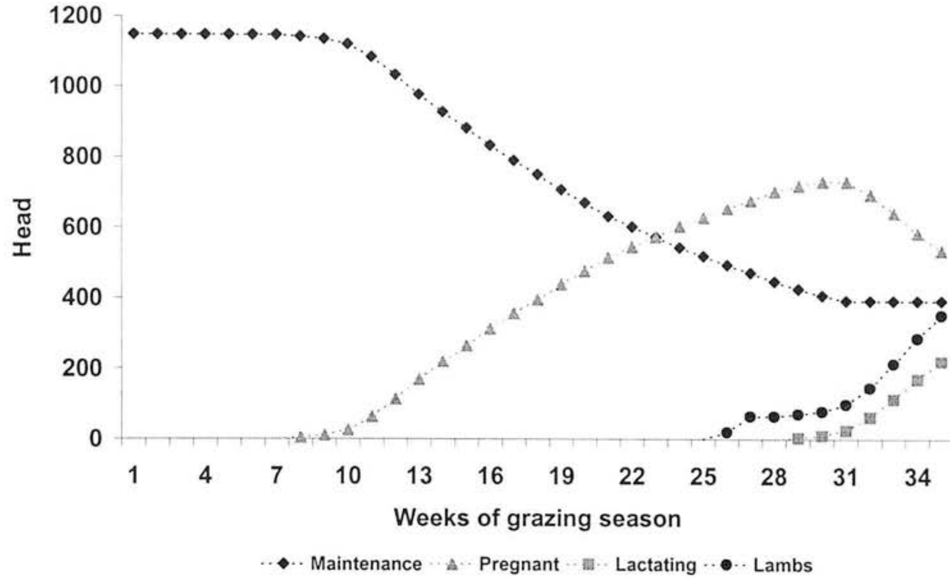


Figure 6-10 Population dynamics throughout the grazing season for all the ewes and lambs in Coajomulco's flocks as produced by the simulation model

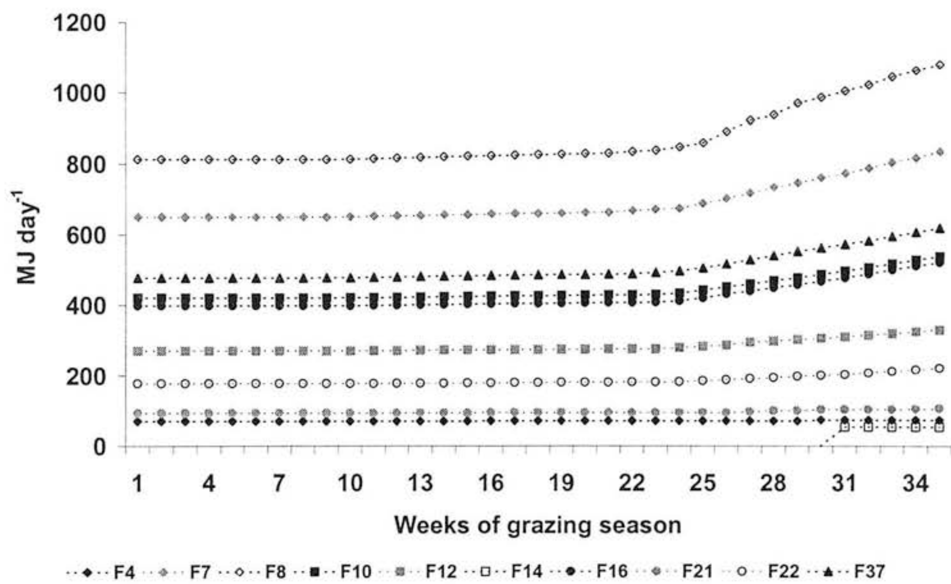


Figure 6-11 Changes throughout the grazing season in ME requirements by ten different flocks of Coajomulco as produced by the simulation model

Chapter 7

Optimisation Model of the Spatial Use of Grazing Resources by Coajomulco's Sheep Flocks

7.1 Introduction

In this chapter the information and methodologies presented throughout this thesis are integrated into a linear programming model. This model was developed to identify the distribution of sheep flocks over the grazing areas in Coajomulco such that the use of local grazing resources were optimised. Chapter 3 summarised the conflict of interests that have prevailed in Coajomulco since the area was declared protected and agricultural activities were regulated. The first section of this chapter considers the concept of sustainability of the forest-sheep interactions in Coajomulco. Section 7.3 presents the methodological framework and sections 7.4 to 7.6 consider the data required for the development of the model.

The optimisation model was developed to reconcile conservation objectives with those of the local sheep farming system. The optimisation model presented here aimed to identify a feasible pattern for the distribution of flocks over the grazing areas that was sustainable for both sheep and the forest ecology.

The first issue to be addressed was to define sustainable sheep production and sustainable forest ecology. In this thesis sustainable sheep production is considered within the socio-economic context of Coajomulco's grazing system. Thus, the smallholder system functioning is understood to be sustainable if the sheep production is perpetuated as an economically viable activity within which the forest provides an affordable source of grazing material. However, the sustainability of the plant-animal interactions in an ecological framework is more complex to define. It requires evidence of the impacts of sheep on the dynamics of plant communities and their long-term effects. The following section is devoted to addressing this issue.

7.2 Sustainability of the plant-animal interactions in grazing systems

According to Hodgson and Da Silva (2000), sustainability in grazing systems refers to the maintenance of productivity and stability in the soil, plant and animal component of the system. This definition agrees with that of Caughley (1979) and Caughley and Lawton (1981) who proposed that the concept of "ecological" carrying capacity could be differentiated from that of "economic" carrying capacity. Ecological carrying capacity is then understood to mean that the ecological components of the system can persist in a stable state over time under a given grazing pressure.

A number of theories have been put forward regarding the response of plant communities to disturbance by grazing. Several authors have considered the disturbance of plant communities and its effect on their stability. It is argued that disturbance can be followed by an equilibrium or non-equilibrium state. Thus, a system is stable if all variables either return to equilibrium values after the disturbance (Walker and Noy-Meir, 1982; Pimm, 1984; Tainton *et al.*, 1996) or equilibrate in a new "domain of attraction" (no changes can occur without major intervention) (Noy-Meir, 1975). On the other hand, if a steady state is never achieved, the system is said to be in a non-equilibrium state (Walker and Noy-Meir, 1982; Tainton *et al.*, 1996).

Another issue to be considered in the understanding of sustainability is that plant communities in equilibrium may be identified as being resilient or non-resilient (Holling, 1973; Peterson *et al.*, 1998). In this context, a resilient system is able to return quickly to its equilibrium once the disturbance has been removed. The level of resilience is related to how much disturbance can be absorbed without the system crossing a threshold into some other equilibrium position or "domain of attraction" (Anderies *et al.*, 2002).

It is known that grazing sheep modify the patterns of succession in the understorey vegetation of temperate forests (Hester *et al.*, 1996; Garin *et al.*, 2000). Historically, human disturbance has produced a subclimax state in the forest of Coajomulco. The findings in previous chapters (4 and 5) regarding differences of species composition and biomass in relation to the level of disturbance can be considered as evidence of this state. Under the constraints of the current study, with information only being available for one grazing season, it is impossible to state whether the differences found in the plant communities were the consequences of a dynamic event, or were merely a series of stable states. Further data over a number of seasons would be required to establish whether or not the system was showing a dynamic change of state. However, it can be assumed that the plant communities of the understorey vegetation are likely to be in a state of equilibrium. Furthermore, resilience can also be attributed to the system. Tainton *et al.* (1996) suggested that systems in equilibrium are more likely to occur where rainfall is relatively consistent and predictable, and where the community is comprised totally or largely of perennial plants. As mentioned in Chapter 4, the plant species in Coajomulco are largely composed of geophytes, hemicryptophytes and therophytes. This means that the understorey vegetation can regenerate annually when the rainy season starts, after a period of dormancy during the dry season. The dry season provides an opportunity for the disturbance to be removed and for recovery of the equilibrium once the rain starts.

It is important to consider that equilibrium states can be reached at different "domains of attraction" (Anderies *et al.*, 2002). Thus, a plant community that is in equilibrium may not necessarily be in the optimal state from a conservation perspective. Given the regenerative capacity of forests, the question that arises is whether it is possible to enhance the conservation value of Coajomulco's forest through optimal grazing management. To achieve this, monitoring of the dynamics of plant communities and their response to different levels of defoliation is necessary.

Little information is available about optimal levels of grazing pressure on temperate forests. However, Mitchell and Kirby (1990) suggested that grazing levels that produce a woodland with maximum nature conservation value will lie around the moderate to light. It has been suggested that monitoring the response of shrub species that have low tolerance to grazing can be used as an indicator of the degree of disturbance (MCMC, 1998). The association between disturbance of the understorey vegetation with the general condition of the forest ecosystem (including trees) has been identified (Mitchell and Kirby, 1990; Reimoser *et al.*, 1999).

It has been proposed by Jorritsma *et al.* (1999) that threshold of herbivore densities should be assessed in order to estimate the effects of grazing on forest conservation. In a slightly different context, some authors have developed thresholds of grazing pressure based on the percentage of utilisation of plant species. Through the use of a simulation model, Kienast *et al.* (1999) established a threshold of defoliation of 30 to 40 % in a mountain forest. Although developed in heather moorland vegetation, Grant and Armstrong (1993) estimated the threshold of percentage utilisation for good native grass to be 60 % and from 5 to 40 % for heather in different stages of maturity. Similar data was reported by Hodgson and Grant (1985).

Despite the lack of measurements of percentage of utilisation in Coajomulco's plant communities some assumptions can be derived from the sampling process reported in Chapter 5 (Section 5.2). Since only leaves and young stems were collected during the biomass production sampling, some standing biomass was left. The amount of material that remained would depend on the stem-leaf ratio of the plant species, and therefore would be associated with the threshold of percentage utilisation. Although the stem-leaf ratio between species can be variable in highly diverse plant communities, it is generally larger in shrub species (Kurosawa, 1995).

In addition, as reported in Chapter 6 (Section 6.5.1), the botanical composition of the sheep's diet differs from the botanical composition of the edible plant material. Thus, biomass sampling methodology and correction in the biomass by diet selectivity of animals affects the final figure of utilisation percentage, and may produce a low value. Analyses presented further below in Section 7.5.1 looks at these issues.

7.3 Methodological framework for the optimisation model

As mentioned in Chapter 3 (Figure 3-8), the communal grazing land of Coajomulco can be divided into 11 areas (without considering the grazing exclusion zone). It was also mentioned in Chapter 3 that shepherds were able to visit only one of these zones in a given day. This produces spatial and temporal heterogeneity in the distribution of the 38 sheep flocks over the 11 grazing areas. It can be considered that this scenario provoked an irregular grazing intensity that could be detrimental for both sheep and plant communities. Irregular grazing intensity will have affected the ability of each flock to obtain the quantity and quality of food that they require. Furthermore, irregular grazing can create overgrazed patches that are undesirable under the conservation regime of the whole zone. Thus, the model intends to identify the distribution of flocks that can maintain the system in equilibrium. The optimal allocation of each flock to different grazing areas throughout the grazing season will result in the ability of sheep to fulfill their nutritional requirements and in the maintenance of a stable state for the plant communities. The driving logistic of the model was matching forage demand with forage supply as indicated in Voisin's (1959) principles of grazing systems. In this case rather than using dry matter as the linking variable between sheep and forage, metabolisable energy (ME) expressed in MJ was utilised.

The information collected, analysed and presented throughout this thesis was integrated in a relational geodatabase management system (MacDonald,

1999) using ArcGIS© 8.1 (ESRI). Three geodatabases were used to store and handle the model input: i) data related to the sheep element of the system, ii) data related to the plant element of the system, and iii) data related to the abiotic factors of the plant-animal interactions (as described in Chapter 6, section 6.4). The biotic factors of the plant-animal interactions were intrinsically considered in either the plant or animal elements. Figure 7-1 shows the conceptual framework of the model. The content of each geodatabase is summarised below, and although most of the data included in them has already been described in previous chapters, further methodological process will be described as required.

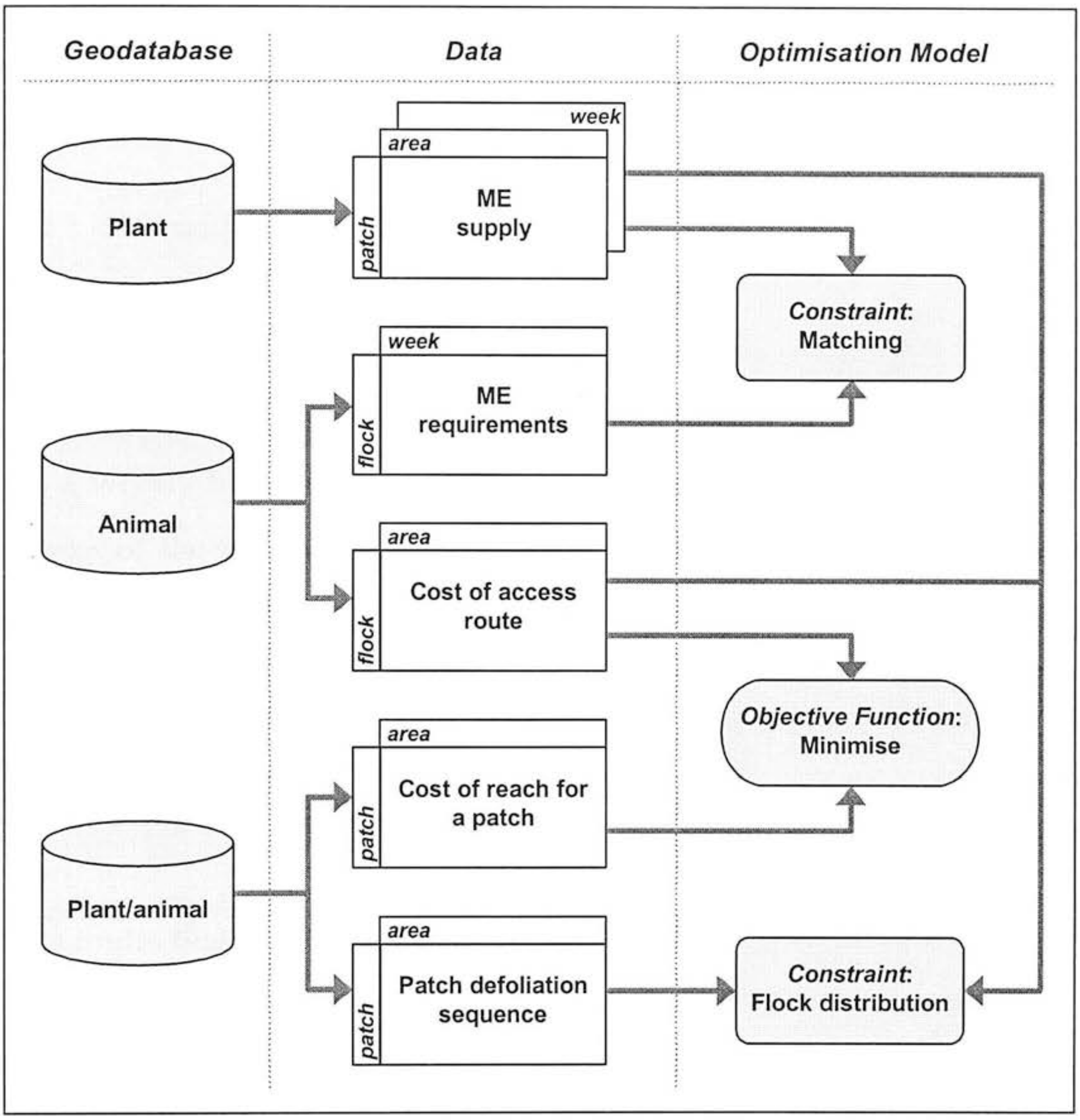


Figure 7-1 Methodological framework for the development of the spatial optimisation model

7.4 Geodatabase for animal-related information

The information regarding the animal element of the system included in the model was comprised of two elements: i) requirements of ME by flock and ii) energy costs for routes of access.

7.4.1 ME requirements of flocks

ME requirements for each flock were derived from the flock dynamics simulation model presented in Chapter 6 (Section 6.7). For the model to run on a weekly basis changes in ME requirements were estimated for the 35 weeks of the grazing season. In the geodatabase, ME requirements were related to the spatial location of each penning site in the agricultural area as shown in Figure 3-7.

7.4.2 Energy cost for access routes

The routes that each flock had to follow from their respective penning sites to the different grazing areas were considered. As it can be appreciated from Figure 3-7 and 3-8, accessibility to grazing areas varied according to the location of the penning site of each flock. For the model to distribute flocks in an efficient way over the grazing zones, it was necessary to consider the cost of accessing each grazing area from the different penning sites.

Methodology

A GIS methodological framework to calculate the relative cost of travelling similar to the one reported in Chapter 6 (Section 6.4) was constructed. Following McCoy's (2001) methodology a CWD routine was applied including the slope and land use cover layer. The location of paths, water courses, trails, roads, urban area and agricultural plots were considered in the analysis. Thus, the most efficient path from each penning site to each grazing area was found.

Figure 7-2 illustrates an example of the layout of the access routes from a penning site to some of the grazing areas. The spatial analysis also produced the profile graph of each route that calculates estimate the horizontal and vertical distance that each route covered. Some examples of the profile graphs are also shown in Figure 7-2.

Quantification of energy costs

The energy cost of sheep walking each of the access routes were calculated based on their horizontal and vertical distances. An energy cost of 2.6 J/kg body weight (BW) and 28 J/kg BW for each metre of horizontal and vertical movement respectively were used as reported by AFRC (1980).

The calculated energy cost of walking each access route was stored in the geodatabase indexed by flock number (1 to 38) and grazing area (1 to 11).

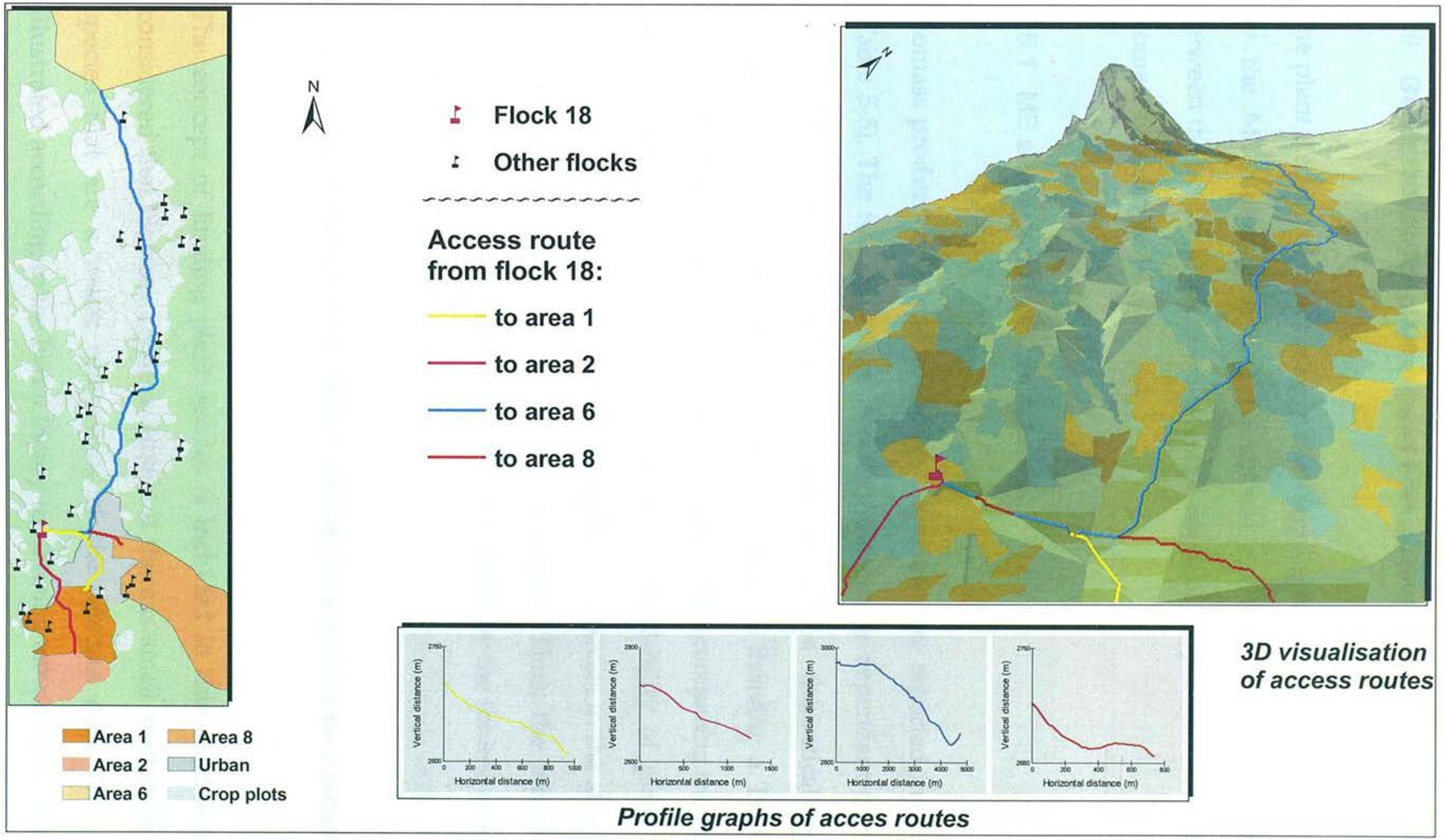


Figure 7-2 Example of the spatial analysis of the access costs illustrating the routes from flock 18's penning site to grazing areas 1, 2, 6 and 8

7.5 Geodatabase for plant-related information

The plant element of the grazing system was represented in the model solely by the ME supply. Previous adjustment derived from the relationship between the botanical composition of the diet and the production of standing biomass was carried out.

7.5.1 ME supply from plant communities

Biomass production data of edible plant species were reported in Chapter 5 (Table 5-5). The rate of utilisation of that biomass is dependant on the diet selected by sheep. In Chapter 6 (Section 6.5) a theoretical botanical composition of the selected diet was calculated by deriving a TCD_{ij} value with Genin and Quiroz's (1993) methodology. When comparing the botanical composition of this theoretical diet with the availability of plant species (Figure 6-7) it was noticed that the proportion of species in the sheep's diet was not the same as the one in the community. Thus, the intake of the theoretical diet can be considered to be constrained by the limited availability of some species.

Methodology to calculate the effect of limiting plant species on biomass intake

The concept of limiting plant species is included in this analysis as it is considered that biomass intake is limited if there is small availability of the species that are a major component of the selected diet. This can be illustrated according to the barrel theory for limiting amino acids (see Figure

7-3). The content of the barrel represents the biomass intake, with the rim of the barrel indicating the maximum biomass available in the plant community and each of the staves representing the relative abundance of plant species. If one stave is shorter than the others (limiting plant species in the community), the barrel can only be filled to the level of the shortest stave. In other words, defoliation in a given plant community cannot proceed beyond the rate at which the limiting plant species is available.

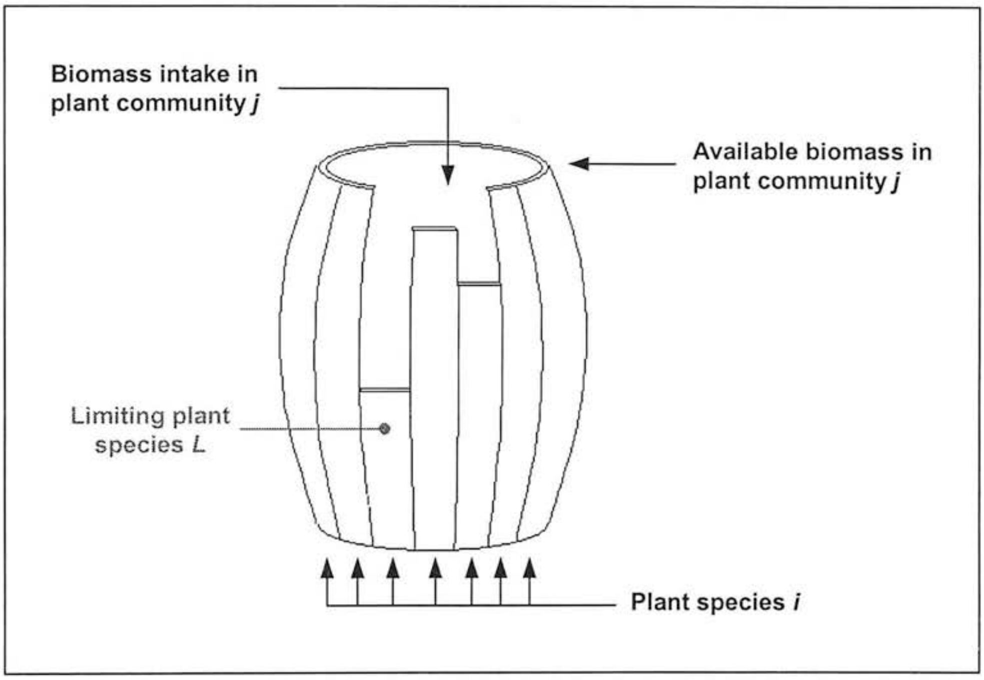


Figure 7-3 Barrel theory illustrating the effect of the limiting species on biomass intake

The adjusted biomass intake according to the abundance of the limiting species in each plant community was obtained by multiplying the adjusted contribution of plant species *i* ($DIET_{ij}$) by the edible biomass in the plant community *j*. $DIET_{ij}$ was therefore calculated as:

$$\mathrm{DIET}_{ij} = F_j \times \mathrm{TCD}_{ij} \tag{7-1}$$

where,

$$F_j = \frac{R_{\mathrm{L}j}}{\mathrm{TCD}_{\mathrm{L}j}} \tag{7-2}$$

and where,

$$\mathrm{L}_j = \min\{R_{ij} - \mathrm{TCD}_{ij}\} \tag{7-3}$$

where, F_j was the adjustment factor in plant community j; TCD was the theoretical contribution of species i to the diet in plant community j (Equation 6-7); R was the relative abundance of species i in plant community j; and L was the limiting species in plant community j.

Results

The biomass results shown in Table 7-1 are the product of the edible biomass production multiplied by DIET_{ij}. These values represented the biomass that is defoliated by sheep if the theoretical diet is consumed. As can also be seen in Table 7-1, the percentage of utilisation of plant material varied from 11.8 to 56.1 %. These figures indicate the grazing intensity that sheep would produce if they were able to chose the theoretical diet in each plant community.

The supply of ME in the theoretical diet was derived in Chapter 6 by means of simulation with the DYNAFEED model (Table 6-1). In the geodatabase, ME values for each plant community were stored in a layer with a cell size of 20 × 20 m. Figure 7-4 shows the spatial distribution of the ME pool. Total values of ME in every patch (where a patch is a cell in the GIS layer) of each plant community are also shown in Table 7-1. ME values are expressed as MJ/400 m^2 as a result of the cell size used in the analysis. These adjustments were also applied to the vegetation regrowth to estimate ME supply through the grazing season.

The percentages of utilisation of the understorey vegetation obtained with this analysis were considered to provide suitable guidance for the estimation of the system's sustainability. On one hand, they are a consequence of a theoretical diet that maximises the energy intake of sheep flocks; and on the other, they are relatively low and are assumed not to lead to a level of overgrazing. Thus, the ME pool required as an input for the optimisation model was obtained directly from the analysis presented in this section.

Table 7-1 Adjusted biomass production, level of utilisation and ME supply/cell by plant community in the adjusted intake as produced by the limiting species in each community

Plant community	Edible biomass (kg/ha)	Level of utilization (%)	ME Supply (MJ/cell*)
Woodland class A	183.4	39.7	60.2
Woodland class B	166.2	33.2	57.8
Woodland class C	28.8	18.5	9.9
Woodland class D	181.8	56.1	60.9
Woodland class E	262.8	51.9	92.5
Woodland class F	60.0	18.7	20.8
Woodland class G	199.2	35.5	65.3
Grass and Scrub class	42.1	43.4	48.3

*As calculated for the edible biomass in a 400 m^2-cell

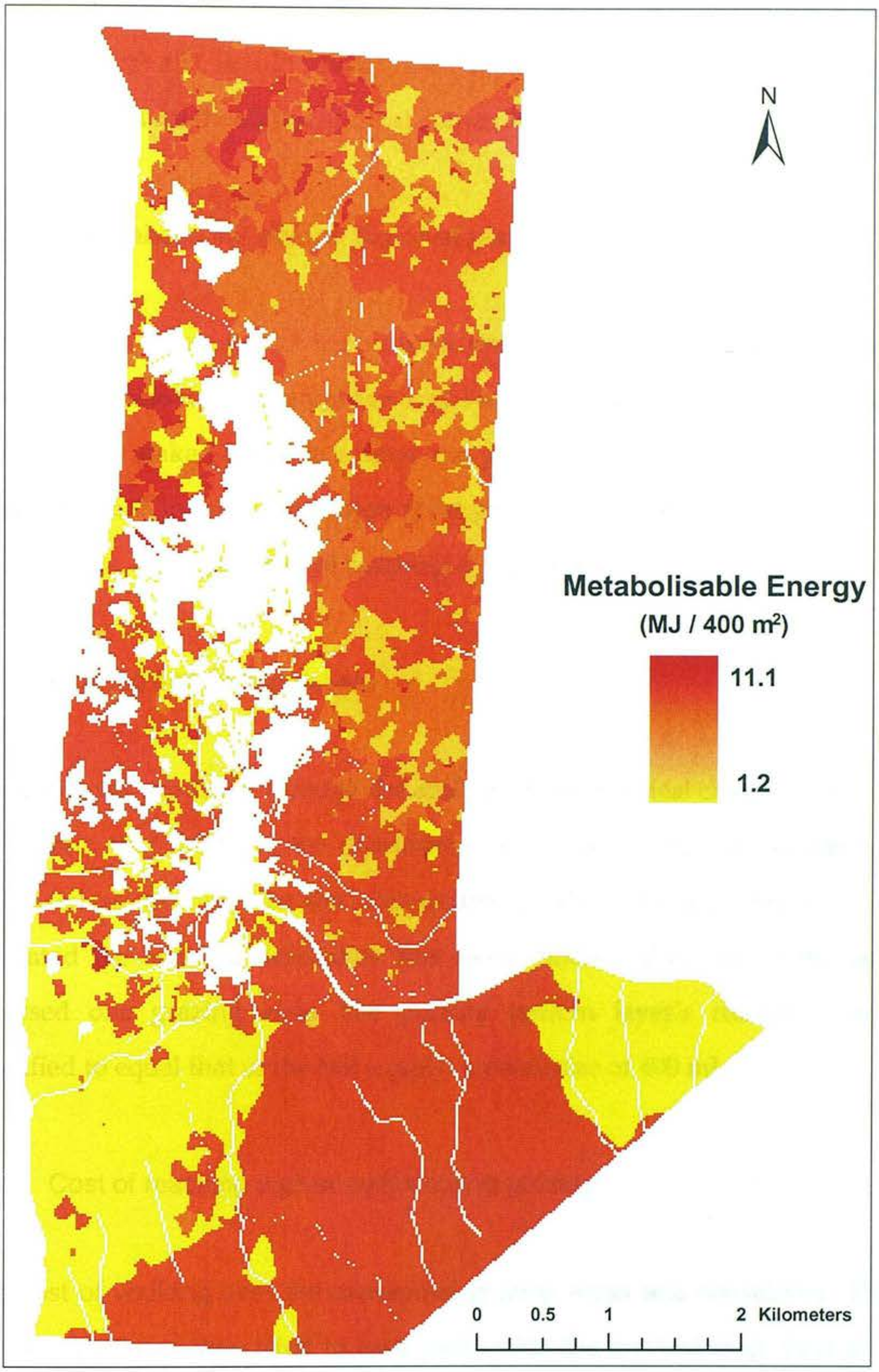


Figure 7-4 Spatial distribution of the pool of ME at the beginning of the grazing season over the grazing communal land as represented by the plant geodatabase

For the development of this model, it was assumed that if sheep consumed this theoretical diet, would result in overall levels of defoliation between 18.5 and 56.1 % across the different plant communities.

7.6 Geodatabase for abiotic factor of plant-animal interactions

Although the plant-animal interactions were discussed in the last chapter, this geodatabase was named in this way because it contained the information that spatially linked both the animal and plant geodatabases. Two elements were contained in this geodatabase: i) the grazing distribution pattern in each grazing area, and ii) the cost of reaching a grazing patch.

7.6.1 Grazing distribution pattern

The GIS layer produced through the analysis of the physical characteristics of the terrain that influence the distribution of flocks (Chapter 6, Section 6.4) was used as an input for the optimisation model. This layer (Figure 6-5) indicated the order of defoliation that sheep flocks follow once they have accessed one grazing area. The grazing pattern layer's resolution was modified to equal that of the ME supply: a patch size of 400 m^2.

7.6.2 Cost of reaching a given patch during grazing

The cost of walking over the communal grazing areas was considered. This walking cost was associated to each patch with the methodology described below.

Methodology

In each grazing area, the strip where the access routes from the penning sites converged was considered the "entrance" to the grazing area. For the optimisation model to consider the cumulative cost from the "entrance" of each zone it was necessary to calculate the energy cost of walking the horizontal and vertical distances between each patch.

The horizontal distance between each patch was dependant on the way it was walked (i.e. whether horizontally, vertically or diagonally). In this case, the diagonal distance between patches was used, so that it was calculated as the square root of the sum of squares (diagonal distance for a 20 × 20 m cell is 28.28 m). The vertical distance between patches was calculated from the percent of slope layer of Figure 6-3. Thus, the vertical distance was obtained:

$$\text{vertical distance} = \text{horizontal distance} \times \text{slope}/100 \qquad (7\text{-}4)$$

Energy cost of walking each patch was calculated with the values reported by AFRC (1980).

Results

Figure 7-5 shows the results of the estimation of cost of walking each patch.

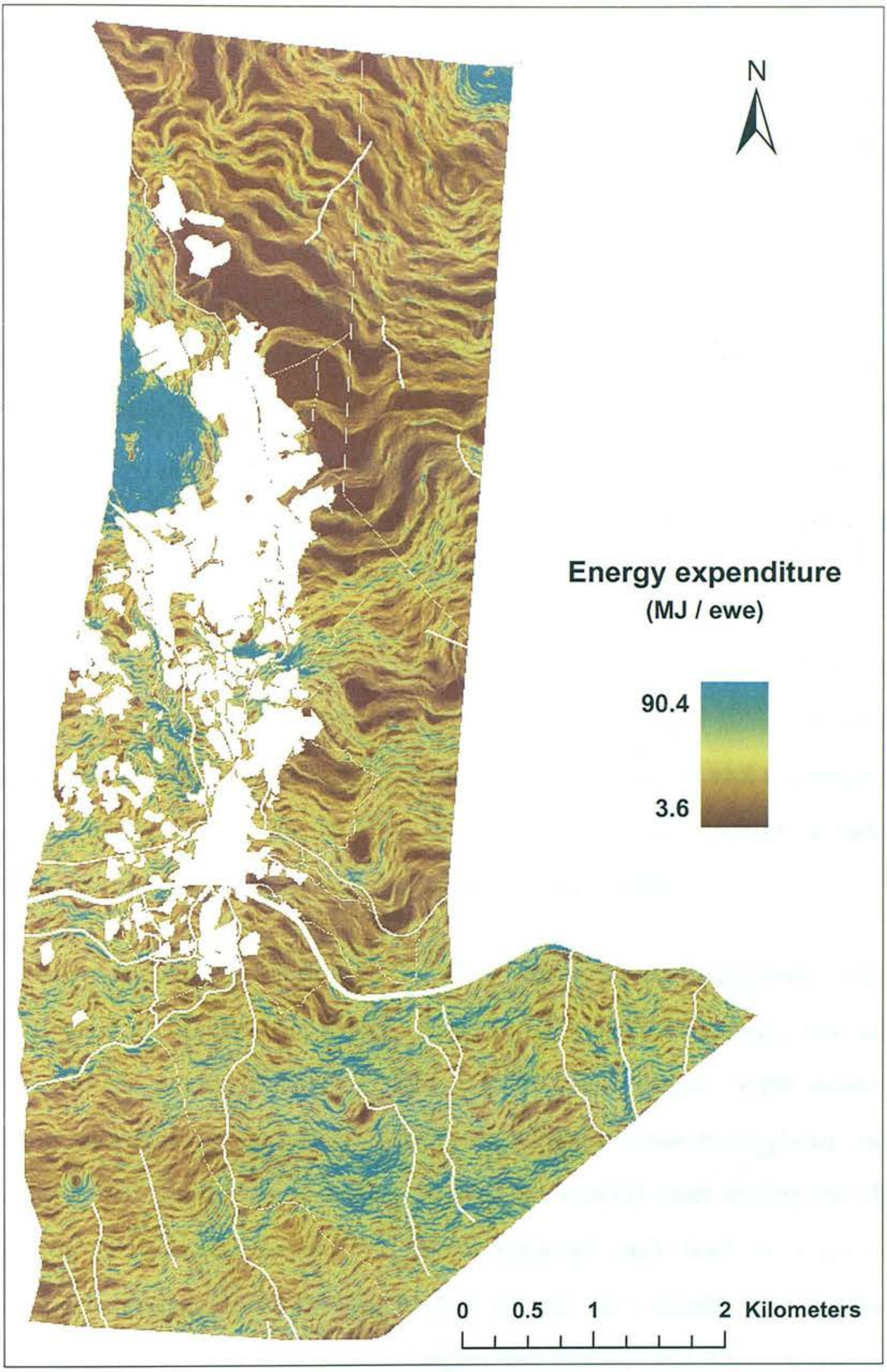


Figure 7-5 Cost of walking each 400m^2-patch over the communal grazing area as represented by the geodatabase for animal-plant interactions

7.7 Optimisation model

The methodology described in this section aimed to provide an initial approach towards the optimisation of Coajomulco's grazing resources.

The optimisation model was developed using linear programming (LP) with Xpress-MP© 13.0 (Dash Associates). Following the basic structure of any LP structure (Dent *et al.*, 1986, 1994), the model included: i) a set of variables that described the system's elements and activities, ii) a single linear expression to be maximised or minimised, and iii) a series of constraints in the form of linear expressions that defined the system's functioning.

This approach was selected for this thesis as the simplest and most straightforward method for linking simulation models and GIS with the optimisation model. In addition, input data could be changed and reassessed relatively easily during the process of validation and generation of new coefficients that represented the heterogeneity of the system.

The mathematical representation of the plant-animal interactions was centred around the sheep's energy requirements and the energy cost of walking to the available "feeding stations". The final output of the model was the allocation of each flock to different grazing areas throughout the grazing season. The model was set up to run in a weekly basis during the 35 weeks of the grazing season. The model assigned each flock to a given grazing area and modified the distribution pattern on a weekly basis in the most cost-effective way. The model output was then loaded into the GIS to visualise the results.

7.7.1 Methodology

Definition of variables for elements and activities

The variables that represented the animal element of the system in the model were:

$$MEREQ_{fw} \tag{7-5}$$

where, $MEREQ_{fw}$ was the requirement of ME by flock f in week w.

$$HEAD_{fw} \tag{7-6}$$

where, $HEAD_{fw}$ was the number of head in flock f in week w.

$$ROUTE_{fa} \tag{7-7}$$

where $ROUTE_{fa}$ was the cost of flock f walking the access route to grazing area a.

Variables $MEREQ_{fw}$ and $HEAD_{fw}$ were produced by the flock simulation model, whilst variable $ROUTE_{fa}$ was produced by the GIS methodology described earlier in this chapter.

The variables that represented the plant communities were:

$$MESUP_{paw} \tag{7-8}$$

where, $MESUP_{paw}$ was the supply of ME from the patch p in the grazing area a in week w.

$$RGWTH_{paw} \qquad (7\text{-}9)$$

where, $RGWTH_{paw}$ was the ME supply contained in the biomass regrowth of the patch p in the grazing area a estimated for the week w.

$MESUP_{paw}$ was calculated in Section 7.5.1 from the theoretical contribution of plant species to the diet, adjusted by the limiting species in each plant community. $RGWTH_{paw}$ was derived from the ME content in each plant community adjusted to the biomass regrowth calculated in Chapter 5 (Section 5.3).

Finally, the variable that represented the abiotic factors of the plant-animal interactions was:

$$REACH_{pa} \qquad (7\text{-}10)$$

where, $REACH_{pa}$ was the cost of reaching patch p in grazing area a.

$REACH_{pa}$ was calculated as described in section 7.4.2.

The grazing process was represented in the model by three activities included in the variables:

$$SITE_{paw} \tag{7-11}$$

$$ASSIGN_{faw} \tag{7-12}$$

$$DEFOL_{faw} \tag{7-13}$$

where, $SITE_{paw}$ was the binary variable that mapped the access to patch p in the grazing area a in week w; $ASSIGN_{faw}$ was the binary variable for the distribution of flock f in the grazing area a in the week w; and $DEFOL_{faw}$ was the variable to locate flock f in grazing area a in week w.

Objective function

The model was built to identify the best distribution of flocks on the grazing areas that minimised the energy cost of supplying each flock with its ME requirements through grazing. The costs involved in the grazing process were divided in two: i) the cost of walking the access route that linked the penning site with the "entrance" of the grazing area, and ii) the cost of walking the selected grazing area until the necessary number of patches to supply the ME requirements were walked.

The objective function to be minimised thus became:

$$\sum_{f}\sum_{a}\sum_{w} ROUTE_{fa} \times ASSIGN_{faw} +$$

$$\sum_{f}\sum_{p}\sum_{a}\sum_{w} HEAD_{fw} \times REACH_{pa} \times SITE_{paw} \quad (7\text{-}14)$$

Constraints

Two constraints were used to ensure that the ME supply was larger than the ME demand for all flocks. First, the constraint *MATCH1* was used to defoliate as many patches *p* as necessary to fulfil the ME requirements for all:

$$MATCH1_{(a=1:\max a, w=1:\max w)} : \sum_{f} MEREQ_{fw} \times ASSIGN_{faw} - \sum_{p} MESUP_{paw} \leq 0 \quad (7\text{-}15)$$

Subsequently, the constraint *MATCH2* assured that the supply in a given week is obtained from only one area. This was possible because *DEFOL* was linked to the binary variable *ASSIGN* through the constraint *REMAIN* below in Equation (7-18):

$$MATCH2_{(f=1:\max f, w=1:\max w)} : \sum_{a} DEFOL_{faw} \geq MEREQ_{fw} \quad (7\text{-}16)$$

The constraint *PERMIT* determined that each flock could only be assigned to one grazing area during a given week through the use of the binary variable *ASSIGN*:

$$PERMIT_{(f=1:\max f, w=1:\max w)} : \sum_{a} ASSIGN_{faw} \leq 1 \quad (7\text{-}17)$$

Subsequently, the constraint *REMAIN* prevented defoliation from taking place in grazing areas other than those previously assigned by PERMIT. The number 10^{10} was used to force the binary variable *ASSIGN* to subtract the real variable *DEFOL*. Thus:

$$REMAIN_{(f=1:\max f, a=1:\max a, w=1:\max w)} : DEFOL_{faw} - 10^{10} \times ASSIGN_{faw} \leq 0 \qquad (7\text{-}18)$$

It was considered that flocks made use of the standing biomass during the first eight weeks of the grazing season. The plant regrowth process was summarised in seven-week regrowth periods. In this way, the ME supply was refilled at week 9, week 16, 23 and 30. The supply of ME was thus represented by a set of constraints, where *EMPT* updated the supply of ME according to the defoliation that took place in *w*-1; and *FIL* included regrowth. Thus:

$$EMPT_{(p=1:\max p, a=1:\max a, w=1:\max w)} : MESUP_{paw} - SITE_{pa(w-1)} \times MESUP_{pa(w-1)} \leq 0 \qquad (7\text{-}19)$$

$$FIL_{(p=1:\max p, a=1:\max a, w=9,16,23,30)} : MESUP_{paw} = MESUP_{paw} + RGRWTH_{paw} \qquad (7\text{-}20)$$

7.7.2 Results

Table 7-2 shows a summary of the model output as reported by the binary variable $ASSIGN_{faw}$. In the first week of the grazing season as well as when regrowth was included (weeks 9, 16, 23 and 30), $ROUTE_{fa}$ was the variable that mainly influenced flock distribution. As the grazing season progressed, $REACH_{pa}$. became of greater importance in the allocation process. Figure 7-6 to 7-8 show the pattern of use at three different stages throughout the grazing season.

The pattern of use of the grazing resources produced by the model can be perceived as sustainable for the ecology of the system, although a better representation by the model of the effect of walking long distances on the grazing behaviour of sheep is needed. In this context, it is important to mention that in this approach, the energy requirements were not modified by the energy spent in walking. Thus, especially at the end of the grazing season, walking long distances to reach ungrazed patches would have an effect on ME requirements and selection of the diet that this model did not account for. It can be visually understood by Figure 7-8 that the grazing exclusion zone did affect the distances that were necessary to walk in order to obtain grazing. Further analysis of the effects that the grazing exclusion zone has had on both the supply of ME and the energy costs of grazing can be carried out with this methodology.

7.8 Sources of variation that can affect the model output

The model produced a theoretical managerial regime for the communal grazing land of Coajomulco where the energy requirements of sheep were met under a grazing pattern that did not affect the ecological sustainability of the local plant communities. This model thus brought together information related to the animal and plant elements of the grazing system, expressing their energy values as part of a dynamic biological system. The optimisation model was therefore aimed at producing the most cost-effective grazing pattern in which energy supply meets energy demands.

Table 7-2 Allocation of sheep flocks in the different grazing areas of Coajomulco throughout the grazing season as produced by the optimisation model with the variable $ASSIGN_{fa}$ (Equation 7-12)

	Week																																		
Flock	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**
1	7	6	5	7	6	6	6	7	6	6	6	6	6	6	7	6	6	6	6	6	6	7	6	6	6	6	6	6	7	6	4	6	7	6	6
2	10	2	1	10	2	1	1	10	2	3	1	2	3	9	10	2	1	1	2	3	9	10	2	1	1	2	3	9	10	2	4	8	6	8	10
3	7	6	1	7	6	6	1	7	6	6	4	6	6	6	7	6	6	4	6	6	6	7	6	6	4	6	6	6	7	2	4	6	3	6	7
4	4	3	1	4	3	11	2	4	3	11	1	2	3	9	4	3	11	1	2	3	9	4	3	11	1	2	3	9	4	3	4	6	3	4	8
5	4	2	1	5	2	11	1	5	2	11	1	4	9	9	5	2	11	1	4	9	9	5	2	11	1	4	9	9	5	2	4	6	3	4	8
6	7	8	1	7	5	4	7	7	5	4	7	2	5	5	7	5	4	7	2	5	5	7	5	4	7	2	5	5	7	2	4	8	11	8	7
7	8	8	1	8	10	1	1	8	10	2	1	4	3	4	6	10	1	1	4	3	4	8	10	1	1	4	3	4	8	2	8	8	7	8	10
8	7	6	4	7	6	6	7	7	6	6	7	6	6	5	7	6	6	7	6	6	5	7	6	6	7	6	6	5	7	6	4	6	11	6	7
9	4	2	1	7	2	1	1	3	2	1	1	2	3	9	7	2	1	1	2	3	9	7	2	1	1	2	3	9	7	2	4	8	3	4	8
10	7	6	3	7	6	6	7	7	6	6	7	6	6	5	7	6	6	7	6	6	5	7	6	6	7	6	6	5	7	6	4	6	7	6	7
11	4	2	1	4	2	1	2	4	2	2	1	2	3	4	4	2	1	1	2	3	4	4	2	1	1	2	3	4	4	2	4	8	7	4	8
12	7	2	1	7	2	1	1	7	2	2	10	2	3	9	7	2	1	10	2	3	9	7	2	1	10	2	3	9	7	2	10	8	11	4	8
13	4	6	1	7	6	6	1	7	6	6	1	2	6	9	7	6	6	1	2	6	9	7	6	6	1	2	6	9	7	2	4	6	7	6	6
14	7	6	3	7	2	11	10	7	2	11	1	2	9	9	7	2	11	1	2	9	9	7	2	11	1	2	9	9	7	2	4	6	7	4	8
15	8	2	1	8	11	1	2	8	2	1	10	2	3	9	8	2	1	10	2	3	9	8	2	1	10	2	3	9	8	2	10	8	6	4	8
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17	5	2	2	5	2	4	2	5	2	4	1	2	3	9	5	2	4	1	2	3	9	5	2	4	1	2	3	9	5	2	4	8	7	4	8
18	4	3	1	4	3	11	4	4	3	11	1	2	9	9	4	3	11	1	2	9	9	4	3	11	1	2	9	9	4	3	4	6	11	4	8
19	4	2	1	4	2	11	1	4	2	11	1	2	9	9	4	2	11	1	2	9	9	4	2	11	1	2	9	9	4	2	4	6	3	4	8

Table 7-2 *Continued*

	Week																																		
Flock	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**
20	7	2	3	6	11	11	4	6	11	11	10	4	11	7	6	11	11	10	4	11	7	6	11	11	10	4	11	7	7	11	10	3	3	4	7
21	7	6	1	1	3	1	4	1	3	11	10	4	11	7	4	3	1	10	4	11	7	1	3	1	10	4	11	7	7	11	10	3	3	4	7
22	7	2	2	1	3	1	4	1	3	2	1	4	11	7	7	3	1	1	4	11	7	1	3	1	1	4	11	7	7	11	10	3	3	4	7
23	1	2	1	9	3	1	4	9	3	11	10	4	11	7	9	3	1	10	4	11	7	9	3	1	10	4	11	7	1	11	10	3	4	4	7
24	4	9	10	1	3	10	10	1	3	10	1	9	7	7	4	3	10	1	9	7	7	1	3	10	1	9	7	7	5	10	10	3	6	7	6
25	7	11	11	1	11	11	2	3	11	11	10	4	11	7	7	11	11	10	4	11	7	1	11	11	10	4	11	7	7	11	4	5	3	4	7
26	4	2	6	1	3	1	10	1	3	3	1	4	11	7	7	3	1	1	4	11	7	1	3	1	1	4	11	7	4	11	10	3	4	7	7
27	4	6	1	6	4	4	4	6	4	4	4	4	7	7	6	4	4	4	4	7	7	6	4	4	4	4	7	7	5	4	10	5	4	4	11
28	7	6	1	1	4	1	10	3	4	3	10	2	7	7	4	4	1	10	2	7	7	1	4	1	10	2	7	7	7	11	10	5	6	4	6
29	4	6	2	1	3	1	10	3	3	3	10	4	11	7	7	3	1	10	4	11	7	1	3	1	10	4	11	7	5	11	10	3	3	7	10
30	4	1	6	1	3	1	2	3	3	2	7	2	11	4	4	3	1	7	2	11	4	1	3	1	7	2	11	4	4	1	4	3	3	9	9
31	4	3	3	1	11	11	4	1	11	11	10	4	11	7	10	11	11	10	4	11	7	1	11	11	10	4	11	7	4	11	10	3	3	7	10
32	8	2	2	1	11	11	4	3	11	11	10	4	11	7	7	11	11	10	4	11	7	1	11	11	10	4	11	7	8	11	10	3	4	4	9
33	4	3	3	1	3	11	10	1	3	11	7	4	11	7	1	3	11	7	4	11	7	1	3	11	7	4	11	7	4	11	4	3	4	7	9
34	1	3	3	6	3	1	4	6	3	3	10	4	11	7	6	3	1	10	4	11	7	6	3	1	10	4	11	7	1	11	10	3	3	7	10
35	7	6	6	6	11	11	4	6	11	11	4	4	11	7	6	11	11	4	4	11	7	6	11	11	4	4	11	7	7	11	10	3	3	6	6
36	4	6	6	6	3	1	10	6	3	3	10	4	7	7	6	3	1	10	4	7	7	6	3	1	10	4	7	7	5	11	10	3	4	9	9
37	5	6	6	1	11	6	5	1	5	6	5	5	7	7	10	5	6	5	5	7	7	1	5	6	5	5	7	7	5	5	5	5	6	7	6
38	4	3	3	1	3	1	10	1	3	3	10	4	11	7	7	3	1	10	4	11	7	1	3	1	10	4	11	7	4	11	10	3	3	6	9

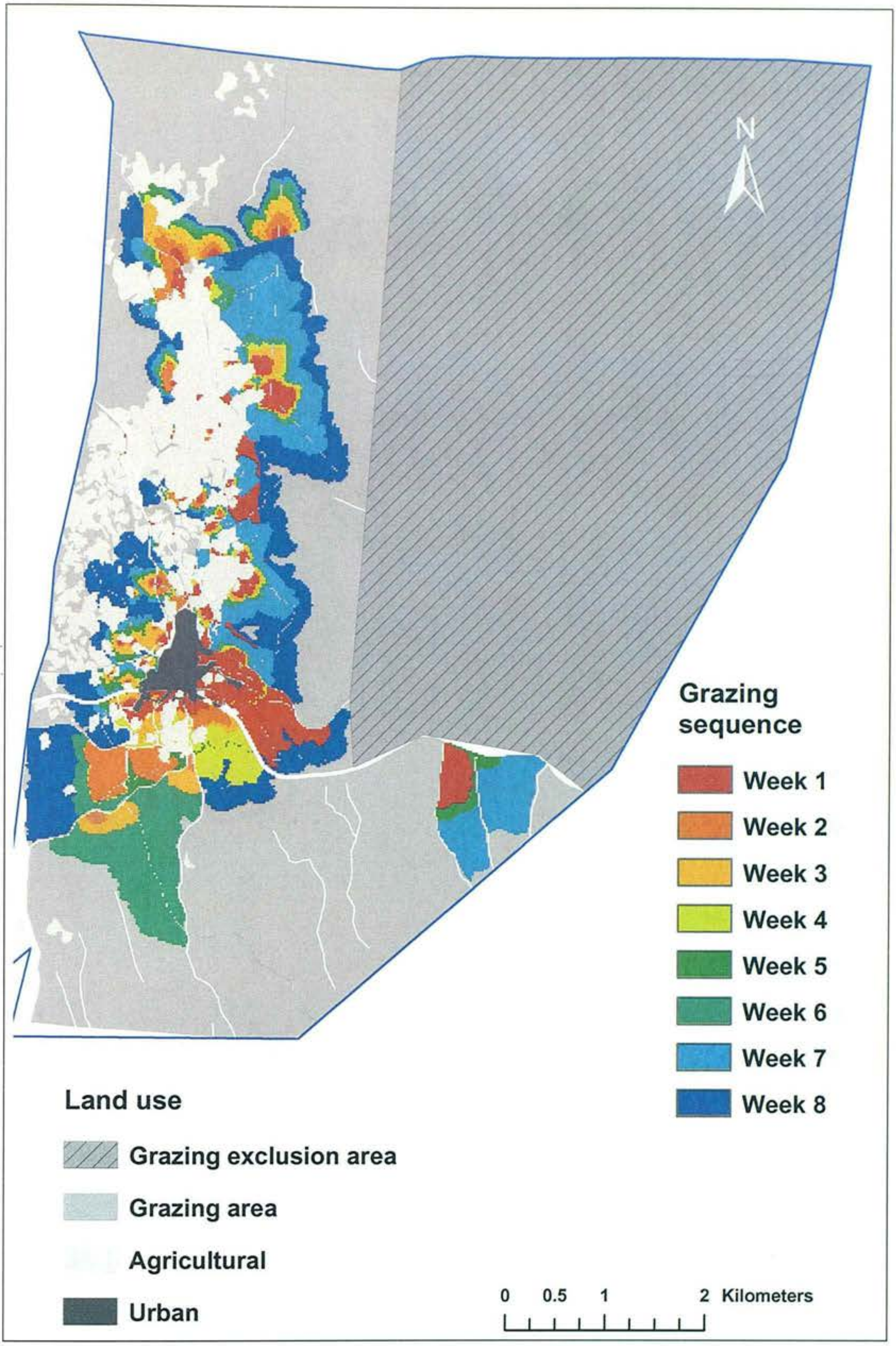

Figure 7-6 Pattern of use over the grazing areas of Coajomulco during the first eight weeks of the grazing season as produced by the optimisation model

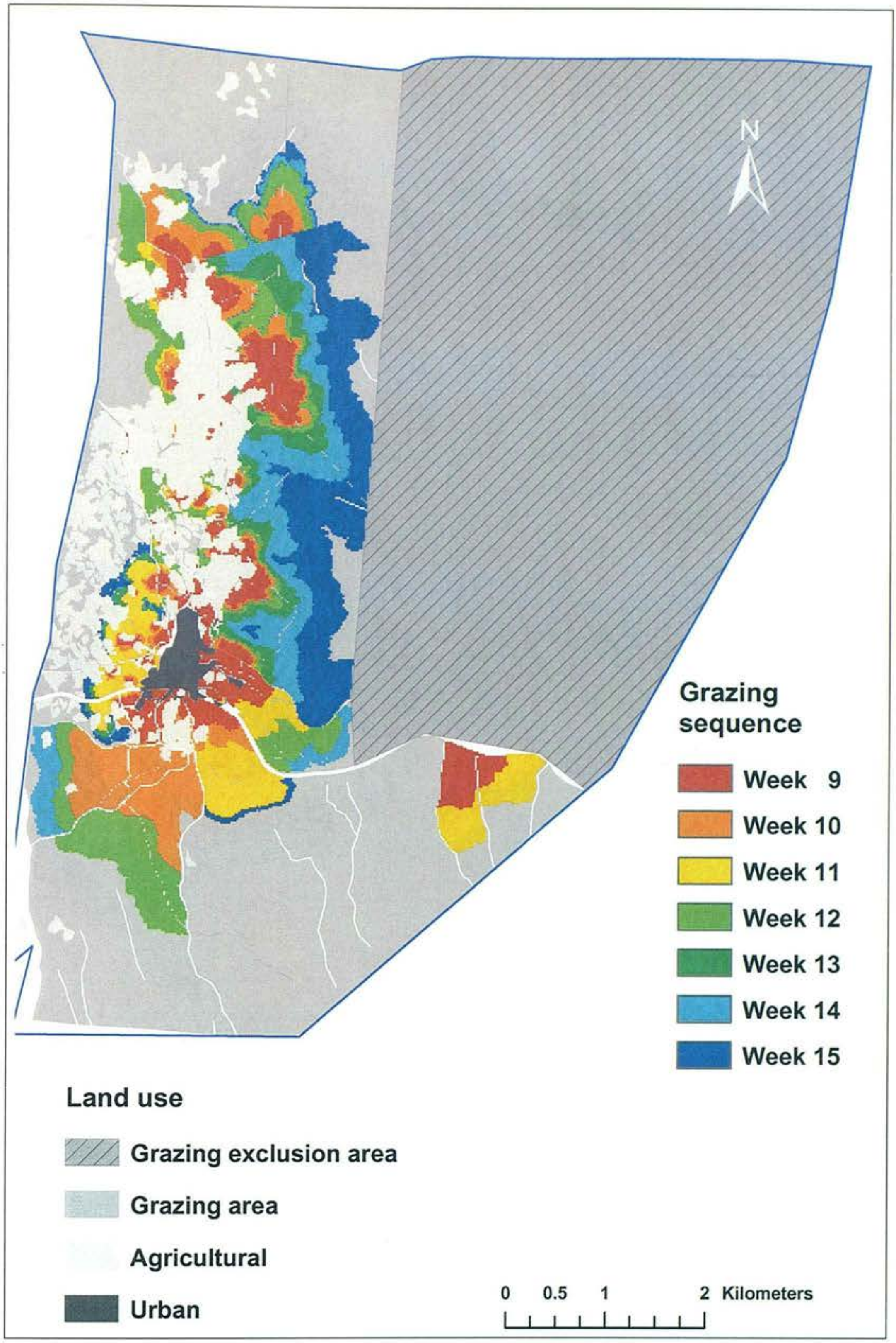

Figure 7-7 Pattern of use over the grazing areas of Coajomulco during the seven weeks after the first plant regrowth was included in the ME supply as produced by the optimisation model

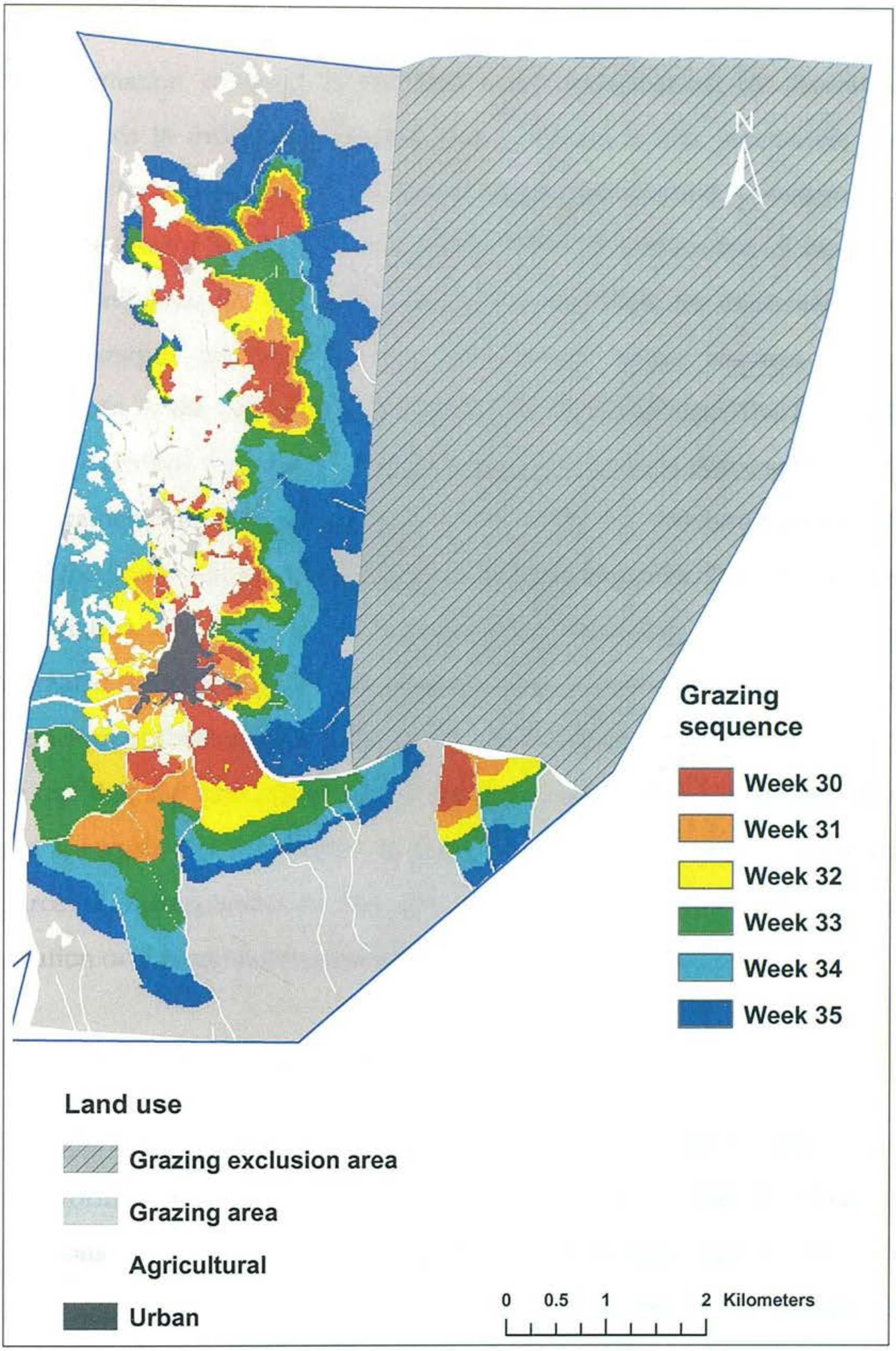

Figure 7-8 Pattern of use over the grazing areas of Coajomulco during the last six weeks of the grazing season as produced by the optimisation model

As was shown through the different methodologies presented in this thesis, the information collected in the field was complemented by theoretical assumptions in order to synthesise and transform it into parameters that expressed the energetic values of forage supply and demand. Consequently, it is of the utmost importance to be aware of the different sources of variation that can influence the values of these parameters. Thus, the implementation of any output produced by the optimisation model requires further exploration of the reliability and accuracy of the input data. The following section describes the most important sources of variation that could modify the parameters used in the analyses in this thesis and that could potentially affect the final output produced by the optimisation model. The main sources of variation are listed below and classified according to whether they originated in the animal or plant element of the systems, or as a result of the interaction of these elements. However, special attention should be given to the fact that the data collected and theoretical assumptions made provided only a snapshot of information of the functioning of the system. The main source of discrepancies in the data will therefore derive from annual variation of biological, environmental and social parameters.

Sources of variation produced by the animal element

Throughout the development of the methodologies presented in this thesis, the information related to the animal element of the system is subject to variations by individuals. Both reproductive parameters used in the flock dynamics model and productive parameters in the DYNAFEED model are subject to variation due to particular characteristics in individuals. Variability in managerial regimes between farmers that can produce different parameters of fertility and prolificacy should also be considered. Special attention should be given to current productive behaviour of the local sheep genotype and the modelled output. In addition, estimates of energy cost of walking under the local environmental conditions and sheep genotype need further exploration.

Sources of variation produced by the plant element

The main sources of variability that are related to the plant element of the system can be grouped into four points: i) source of error during the classification of the satellite image; ii) dynamics of plant communities in response to different grazing pressures; iii) dynamics of plant communities in response to differences in rainfall and temperature; and iv) dynamics of plant communities in response to soil characteristics and other sources of disturbances (e.g. reduction in tree canopy and soil extraction). Furthermore, each vegetation class will respond differently to the sources of variability listed above. Thus, changes in botanical composition and biomass production could take place at a regional scale, at a vegetation class level or even only in isolated patches.

Sources of variation produced by the animal-plant interaction

This source of variation is perhaps the most complex to characterise. The methodologies developed in this thesis are based only on theoretical assumptions that still need further testing. Lack of knowledge about selectivity and digestibility of plant species by sheep is one of the main sources of uncertainty in the model. In addition, allelochemicals and plant toxins are not fully characterised nor their effects on plant digestibility totally understood. The effect of defoliation and trampling on the dynamics of plant communities must also be considered.

7.9 Sensitivity analysis

7.9.1 Introduction

Sensitivity analysis is a common procedure in the development of models, which helps to identify variables with higher influence on the final output of the model (France and Thornley, 1984; Herrero *et al.*, 1999). Carrying out sensitivity analyses provides valuable information regarding the critical components that can affect the modelled representation of the functioning of an agricultural system.

The previous section highlighted some of the sources of variation in the input variables that could have an influence on the final results produced by the model. In this section, a sensitivity analysis is carried out in which some consideration is given to the variation in biomass production estimates and their influence on the grazing distribution pattern produced by the optimisation model. Thus, the sensitivity of model output to variations in biomass estimates was assessed by altering the amount of biomass availability shown in Table 7-1. As was mentioned above, changes in biomass estimates could be obtained within and between vegetation classes. For the illustrative purposes of this section, it was assumed that the degree of variation in biomass production affected all of the different vegetation classes to the same extent.

For the sensitivity analysis, the original biomass production values were reduced and increased by 10%. Changes were made to both the standing and regrowth biomass values. These changes in biomass values were reflected in the energy content of the plant communities. The spatial distribution of the energy values across the grazing areas was adjusted to the new biomass values, as described in Chapter 7 (section 7.5.1). Finally, the optimisation model was re-run with updated values for the variable $MESUP_{paw}$ described in Equation 8-8. Variation in the allocation of flocks across the different grazing areas throughout the grazing season was evaluated by estimating the grazing pressure expressed as the number of flocks per area. The grazing pressure was evaluated at five different stages of the grazing season: the start of the season, and four regrowth periods at weeks 9, 16, 23 and 30 of the grazing season as used in the optimisation model (Equation 7-20).

7.9.2 Results

Figure 7-9 illustrates the results of the sensitivity analysis shown as the difference in number of flocks in each grazing area produced with the adjusted biomass values compared to the original output. It can be noticed that the pattern of flocks' allocation across the different grazing areas was in fact affected by the biomass availability. This difference however was more evident in the scenario where the biomass was in shorter supply. In both scenarios, there were no changes in the allocation of grazing flock at the beginning of the grazing season. Divergences in the distribution of flocks became more evident as the grazing season progressed with a consequent reduction in biomass availability.

It can be inferred that changes in biomass availability directly influence the extent of area that sheep need to defoliate in order to satisfy their ME demands. Thus, the higher the biomass availability, the higher the energy supply and the smaller the grazing patch to be defoliated. It can also be noticed that the model is more sensitive to scenarios where the ME availability becomes scarce i.e. low biomass production or late grazing season. This situation is due to the fact that this optimisation model considers both the energy cost of walking the access routes from the penning sites to the grazing areas and the energy cost of defoliating a given patch of land. Thus, it is when the energy cost of defoliation becomes larger than the energy cost of walking the access route that an alternative grazing area will be considered for relocation.

It is also important to mention that the effect of biomass reduction on the final output was highly influenced by the energy content of the plant communities under study. The ME supply of the plant communities reported in Table 6-2 averaged 9.4 MJ/kg. As reported in Chapter 6, section 6.5.2, the ME requirement produced by DYNAFEED for a 50-kg ewe was 9.8 MJ/day. This figure suggests that any reduction in the biomass availability would require that different grazing patterns were applied for sheep to fulfil their energy requirements.

The sensitivity analysis described above illustrates the need to explore the way in which different sources of variation in the plant and animal elements of the system may affect the output of the model. Further analysis should be carried out for a better understanding of the model's capabilities and constraints.

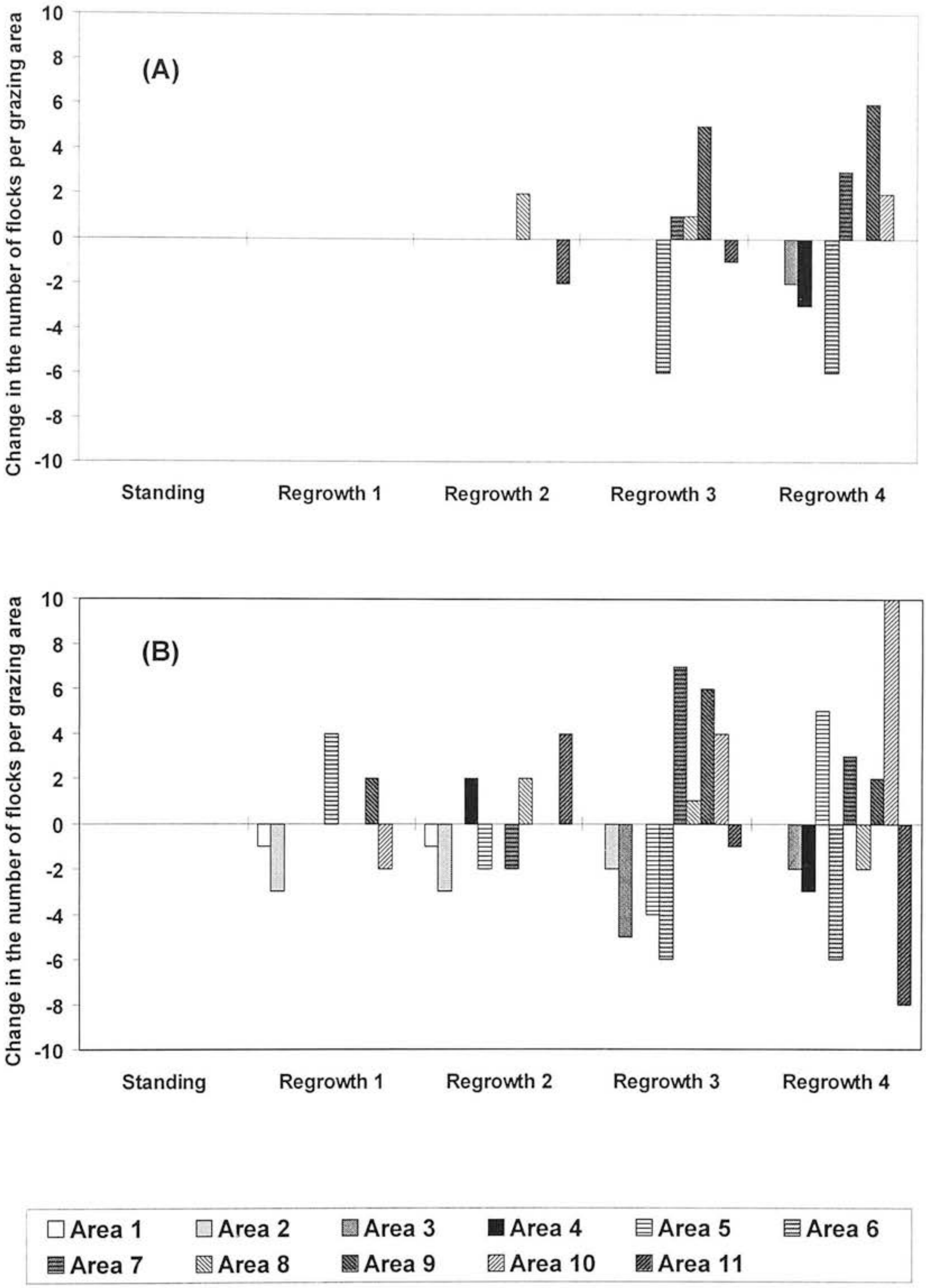

Figure 7- 9 Difference in the number of flocks allocated in each grazing area during 5 periods of the grazing season as obtained by the optimisation model with an increase (A) and a decrease (B) of 10 % of the original biomass availability

Chapter 8

Conclusions

8.1 Introduction

The principal theme of this thesis was concerned with the role of sustainable sheep farming systems in the improvement of smallholding households. A growing problem in many countries, particularly developing countries, is the increasing conflict between environmental and agricultural issues. This situation often leads to either severe environmental degradation or the loss of livelihoods for the people dependant on those natural resources. For these situations to be ameliorated, it is often necessary that intervention takes place at a political and/or local management level.

This thesis therefore addressed this issue with respect to the montane forest of Coajomulco, where sheep farmers and federal authorities have conflicting interests within a protected area. Forestry policies in Mexico have not succeeded in recognising the key role of local populations in the enhancement of conservation and management strategies of forest resources (González-Pacheco, 1985; Bray and Wexler, 1996). At the same time sheep farmers do not necessarily respect the conservation priorities set by authorities who can be unaware of the farmers' real situation.

The contribution of this thesis lay in finding a utilisation rate of the forest grazing resources that was productively satisfactory for sheep farmers and ecologically sustainable for the protected area. The overall objective was to demonstrate how such issues of conflict of resource use can be addressed through the implementation of the analysis techniques and methodologies presented here. Sustainability was not simply perceived as establishing adequate grazing management, but also as a means of increasing, on a wider scale, the impact of sheep production on the whole system. In this context, the rationale was that if the local sheep industry were enhanced with a resulting improvement in the smallholdings' economies, this could result in a reduction of the pressure on farmers to undertake illegal activities on the forest (soil extraction and charcoal making). For example, in Coajomulco, the gross revenue of converting five to six medium size oak trees into charcoal equals the price of three sheep in the market.

8.2 Main findings and areas of further research

The methodologies and analysis of this thesis were grouped into three categories: i) animal elements, ii) plant elements, and iii) plant-animal interactions elements.

8.2.1 Animal element

Regarding the animal element, Chapter 3 described the use of participatory exercises, a survey and direct interviews in the characterisation of the local sheep farming system. The implementation of these methodologies, along with the monitoring of case studies, was done under the framework of Rapid

Rural Appraisal and Participatory Rural Appraisal. This approach was necessary as a response to the lack of information about the productive and reproductive behaviour of Coajomulco's sheep flocks. The necessity of implementing a record keeping system by sheep farmers for the collection of reliable information about sheep performance was evident. This would not only be useful for the farmer himself, but would facilitate the understanding of managerial strategies that affect sheep performance. This knowledge about sheep performance can also be used for the exploration of alternative management regimes through the application of analysis tools (e.g. simulation models, decision support system).

The effect of reproductive seasonality deserves special attention, particularly in connection with other authors' findings for other regions of Mexico (see Galina *et al.*, 1996), where under-nutrition stages of sheep originated during the dry season may provoke a delay in return to reproductive activity. Exploration of the effect of alternative feeding strategies and the trade-off between supplementation costs and better reproductive performance still needs to be addressed. The flock dynamics model presented in Chapter 6 represents a useful tool in the exploration of different feeding strategies and their effect on the distribution of the lambing season. As was derived from the information collected in Chapter 3 and the simulation model, most of the lambing occurs when the grazing season has finished and lactating ewes have to rely on low quality agricultural by-products during the highly-demanding lactation period.

8.2.2 Plant element

The first part of Chapter 4 presented the applicability of remote sensing techniques in mapping the land cover for managing grazing systems. The application of these techniques for assessing the spatial variability of grazing resources was proved to be of great assistance in the assessment of such a highly heterogeneous landscapes as Coajomulco's. Further benefit can be obtained if remote sensing monitoring of grazing resources is carried out as a routine practice. This, along with the necessary groundtruthing for calibration, would provide an invaluable tool for the monitoring of vegetation structure and quality (as described by Edwards *et al.* (1999) and Hill *et al.* (1999)).

Chapter 4 also included the adaptation of the dry-weight rank method of 't Mannetje and Haydock's (1963) for its applicability in the forest understorey vegetation. This modification represented a step forward in the search for feasible methods to monitor the botanical composition of heterogeneous plant communities.

The identification of the botanical composition of the understorey vegetation contributes to the understanding of the ecological value of the area and establishes the first parameters for further analysis of the grazing effects on vegetation dynamics. The response of diversity and biomass production to different levels of disturbance was assessed through a static image. Further research on the population biology of these plant communities is necessary, particularly in the context of the system's stability and resilience to grazing. In this work, the botanical composition was not modified as the grazing season progressed, nor any change of species composition in response to grazing included.

The identification of edible plant species through participatory exercises emphasised the importance of farmers' and shepherds' expert knowledge. The laboratory analysis for nutrient content and degradation kinetics were a major contribution to the knowledge of local grazing systems since it was the first time that many plant species were nutritionally characterised. Further research on the quality of plant species should consider different stages of maturity as well as different plant structures. In addition, it is necessary to characterise the content of anti-nutritional or toxic elements in the area.

8.2.3 Plant-animal interactions

Chapter 6 addressed the heterogeneity of abiotic and biotic factors of the plant-animal interactions. GIS techniques were at the core of the analysis of the abiotic factors, which included the construction of layers that emulated the distribution patterns of sheep flocks over the grazing area.

For the heterogeneity of biotic factors, several theoretical assumptions were made based on studies carried out on vegetation types different to the one under study. Several assumptions were made about the functioning of the underlying mechanisms that were affected by the heterogeneity of multiple plant species communities. Although the effect of multiple plant species on grazing behaviour has been addressed by several authors (e.g. Blackburn and Kothmann, 1989; Armstrong *et al.*, 1997a; Armstrong *et al.*, 1997b; Loewer, 1998), a wider applicability of these authors' approaches is required for the generation of growth and productivity parameters for individual species or vegetation types.

Regarding the relationship between biomass availability and grazing behaviour, although most findings have been produced from studies in plant communities with low numbers of species (e.g. Johnson and Thornley, 1983; Smith *et al.*, 1985; Parsons *et al.*, 1991), the underlying mechanisms were assumed to work similarly in diverse plant communities, as suggested by McFarland *et al.* (1992), Blackburn and Kothmann (1989) and Armstrong *et al.* (1997a). It should be pointed out that this was the area that lacked more reliable evidence for its applicability in Coajomulco's grazing systems. In this context, the model of Genin and Quiroz (1993) represented a suitable alternative for the derivation of a theoretical diet based on the characteristics of the plant species and their relative abundance in the community.

Energy maximisation theory concepts were included in this analysis. Further research is necessary to understand how shepherding can manipulate the energy intake by controlling grazing time and selectivity. This is particularly interesting since it has been recognised that shepherding has an effect on the modification of grazing pressure and its impact on vegetation dynamics (Fuller, 1996; Hope *et al.*, 1996).

The inclusion of simulation models in this study, although limited, is considered to be of the uttermost importance. A simulation model for predicting forage intake and digestion in ruminants was used and a model that simulated the flock dynamics was built. The use of simulation models in agricultural research has been widely recognised as a useful research tool that can assist the decision making process at the farm and regional level (Dent *et al.*, 1994; Edwards-Jones and McGregor, 1994) Furthermore, the capabilities of simulation models to generate scenarios and explore the effects of managerial strategies in the performance of biological systems have been proved to be fundamental in the application of optimisation techniques (e.g. Castelán-Ortega, 1999; Herrero *et al.*, 1999; Booltink *et al.*, 2001). Future research in this context needs to be directed towards the validation of the simulation models presented here for their accurate and reliable use. These models will then be able to be used for the exploration of improved feeding regimes and their impacts on reproductive parameters, lambing percentages and reproductive seasonality.

8.2.4 Optimisation model

Finally, Chapter 7 presented the application of a optimisation routine for the distribution of flocks over the grazing areas of Coajomulco. This optimisation model brought together all the information generated in the previous chapter of this thesis, and represented a first step towards the implementation of more complex and realistic simulation approaches. The development of this model also represented an innovative application of linear programming and GIS techniques in the study of communal grazing resources. In this thesis, this set of tools were used for the first time for the spatial optimisation of grazing distribution patterns.

Further research should be focused on the improvement of the mathematical algorithms utilised for representing and solving the scenario. Special attention should be paid to the use of genetic algorithms, neural networks and other branch-and-bound routines (Woodward *et al.*, 1995; Barioni *et al.*, 1999).

Prior to a reliable and wider use of the model it is necessary to improve the quality of the input data. The importance of carrying out sensitivity analyses has been highlighted in the previous chapter. Some consideration was given above to the means of improving the accuracy of the animal and plant variables that integrated the model. At this stage it is also necessary the model is properly validated. The validation process could be carried out at two different levels. First, formal scientific validation is necessary to ensure the adequate representation of the biological and ecological functioning of the system. Further research on the theoretical assumptions that backed the construction of this model will improve the capacity of the model to produce applicable and feasible results. On the other hand, the model could also be validated at a broader level with the inclusion of the farming community. This participatory validation would entail that farmers and shepherds are actively involved in activities such as data collection, record keeping and monitoring. The involvement of the farming community would also facilitate the identification of key issues for new research and the model's potential to produce realistic and applicable results.

This optimisation model was built with the aim to provide technical advisors and policy makers with a decision-support tool for the study of the traditional sheep farming system that prevails in the temperate region of Mexico. Although it was developed for the specific characteristics of Coajomulco, the core of the methodologies can easily be extrapolated to other regions of central Mexico where sheep farming is practiced under similar conditions. An important advantage in the development of these methodologies and techniques is that all of them can be modified or updated independently from the others. In this way they represent a set of tools that is generic and robust enough to be easily applied under different scenarios. For example: i) information related to the animal element of the model could be easily updated by adjusting reproductive and productive parameters of local flocks, or ii) information about the distribution of plant communities in other regions could be relatively easily included with remotely sensed data.

The optimisation model represents a useful tool for the ex-post and ex-ante assessment of different scenarios. It could, for example, be used to assess the effect of different flock management strategies on both the regional requirements of energy supply and the land capacity to provide it. Thus, effects of changes in lambing season, flock sizes, culling policies and lamb selling can be explored. The model could also be used in the exploration of conservation strategies and/or land use planning. It could also be able to provide a more objective assessment of the real ecological damage produced by sheep grazing in forest areas.

The use of this model in the analysis of smallholder sheep farming systems offers a integral approach to understand the functioning of the system within a holistic framework. Such an approach is often necessary in the design of management strategies and policy making. The successful development and application of these analysis tools in Mexican agriculture will depend on the existence of trained and qualified people. It is of the utmost importance that universities and research centres participate actively in the application of these techniques within the context of Mexican agriculture. Furthermore, it is also necessary that staff at technical advisory institutions and government organisations are, as their end-users, able to apply these techniques. Finally, it must always be taken into account that if the development of these methodologies is based in participatory techniques, farmers should also play an active key role in their application and improvement.

8.3 Final remarks

The study of smallholder sheep farming systems in Mexico requires an integrated approach. This integration has to be understood at two levels: i) participation of farming communities, researchers and policy-makers in the finding of needs and priorities, and ii) at a research level: integration of tools for the analysis of both bio-physical and economic data for the exploration and prediction of the whole system's dynamics.

The importance of smallholder systems in Mexican agriculture should not be underestimated, and continued efforts should be made to sustain their existence. The participation of the scientific community is fundamental in the process of technology transfer and assistance. Of vital importance is the commitment of local, regional and federal governments in the implementation of coordinated and consistent policies to meet the real needs of smallholder agriculture. Finally, but of paramount importance, smallholder sheep farmers have the leading role in the implementation of any technology or success of policy. Thus, their participation and commitment is essential if an integrated development is pursued.

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